



Optical Closed-Loop Propulsion Control System Development

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Prepared under Contract NAS3-26617

National Aeronautics and
Space Administration

Lewis Research Center

August 1998

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076
Price Code: A05

Available from

National Technical Information Service
5287 Port Royal Road
Springfield, VA 22100
Price Code: A05

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1.0 SUMMARY

The overall objective of this program was to design and fabricate the components required for optical closed-loop control of a F404-400 turbofan engine, by building on the experience of the NASA Fiber Optic Control System Integration (FOCSI) program. Evaluating the performance of fiber optic technology at the component and system levels will result in helping to validate its use on aircraft engines.

Five sensed parameters on the F404 engine, two air/gas temperatures, two rotor speeds, and one actuation geometry position, using six different fiber optic sensing techniques, were chosen for testing in the control system. Where possible, more advanced sensors and electro-optic (EO) interfaces were used than those on the FOCSI program to provide improved quality, accuracy, and stability of the optical sensor signals. Component and system design reviews were conducted through the GE Aircraft Engine Chief Engineer's Office. Details of each sensor's design, functionality, and testing are described in this report.

Optical power and signal processing for the fiber optic sensors is provided by EO circuitry consisting of circuit board modules mounted in a chassis assembly designated the EOI (electro-optics interface), with pigtailed optical fibers interfacing with connectors on the EOI wall. Fiber optic cables were fabricated to interconnect the EOI with the optical sensors. Resulting optical sensor measurements are transmitted via electrical digital data to the EOI signal validation/selection software where comparisons are made

with the five normal F404 analog sensor measurements.

The EOI software selects the sensor input source for the F404 ECU (electrical control unit) to be either the normal F404 signals or the optical sensor signals, conditioned to the expected analog format for input to the engine control. Optical signal validation status is based upon parameter range tests, optical sensor built-in tests, and optical versus normal sensor comparison tests. MIL-STD-1553B communication with the EOI enables receipt of software adjustments and switched output signal commands, and transmission of sensor data for monitoring and recording. A GE EOI Software Definition Document is identified as reference 1.

This report includes descriptions of three test plans. The EOI Acceptance Test is designed to demonstrate satisfactory functionality of the EOI, primarily fail-safe throughput of the F404 sensor signals in the normal mode, and validation, switching, and output of the five analog sensor signals as generated from validated optical sensor inputs, in the optical mode. The EOI System Test is designed to demonstrate acceptable F404 ECU functionality as interfaced with the EOI, making use of a production ECU test stand. The Optical Control Engine Test Request describes planned hardware installation, optical signal calibrations, data system coordination, test procedures, and data signal comparisons for an engine test demonstration of the optical closed-loop control.

2.0 INTRODUCTION

Advanced aircraft propulsion control system components must meet increasingly challenging performance requirements, for example, higher accuracy, expanded measurement range, and shorter time response, and endure more severe environmental conditions like higher cycle temperatures. System simplification and weight reduction, and improvements in reliability and maintainability are intensively pursued. Managing cost is a continuous challenge.

NASA has recognized that use of fiber optic technology will provide immunity to EMI (electromagnetic interference), and higher rates of communication. Weight savings is expected through reduced system conductor count, innovative configurations, and reduced complexity. In addition, fiber optic techniques have demonstrated the capability of providing better sensor and system performance and withstanding higher environmental temperatures.

Fiber optic components and systems identified for potential use in aircraft propulsion control systems require moving through stages of technology development. A continuous expectation of better performance and lower cost is needed to sustain development attention towards transition into product. Technology strengths, advantages, and benefits must be identified, emphasized, and applied while weaknesses must be minimized through design improvement.

In 1975, NASA began work to develop fiber optic sensors for use in aircraft propulsion systems. In 1985-86, Phase I of a program called FOCSI (Fiber Optic Control System Integration) was jointly funded by NASA and DoD (ref. 2). This program identified sensor requirements and environments, assessed the status of fiber optic sensor and related component technology, and conceived a total fiber optic, integrated propulsion/flight control system. In 1988, FOCSI Phase II evaluated the electro-optic architecture needed to service the sensors and presented a detailed

design of a preferred system configuration (ref. 3).

In 1990-94, flight prototype, fiber optic sensing system components, including sensors, cables, and electro-optic circuitry for measuring nine parameters on a F404-400 engine were developed (ref. 4). The components were environmentally tested and the system was installed and signals monitored during engine ground and F-18 flight testing at Edwards AFB, CA. The results were significant in demonstrating the technology and developing a database leading to more fully exploring and exploiting its benefits as well as determining the development needed towards product application.

By building on the experience of the previous programs, the purpose of the program described in this report was to design and fabricate the optical and related components and software required to demonstrate "closed-loop control" of a F404 engine during ground testing. This purpose required the following:

1. Optical component design improvements resulting in improved quality, accuracy, and stability of the optical sensor signals/measurements.
2. Development of a control system strategy providing validation of the optical signals and reversion to the normal engine sensor signals should faults in the optical signals or their processing occur.
3. Analysis of the optical sensor signal characteristics and application of compensation required to maintain control stability during optical mode engine operation.
4. Conversion of the optical signals into an analog format compatible with the normal F404 sensor interfaces for input to the engine control.

The present program also included generation of detailed plans for performing a relatively extensive EOI functionality test, an EOI/ECU system test, and a F404 engine ground test demonstration using the hardware and software produced from this program.

3.0 OPTICAL SENSOR DESIGN/TESTING

3.1 T1 TEMPERATURE SENSORS

3.1.1 Allied Signal Design

- **Physical Design Description**

This sensor is identified as Allied Signal Aerospace (South Bend, IN) Model 1502699. Two units were constructed using housings from the same electrical total temperature sensor as described below in paragraph 3.1.2 for the Rosemount optical T1 sensor. Figure 1 shows a typical physical outline. A photograph is shown in Appendix A, Figure 28. The electrical connector was replaced with a MIL-C-38999 Series III connector with two Amphenol 100 micron core fiber optic pins per MIL-T-29504/4. The electrical RTD sensing element was replaced with an optical sensing element. A design review was conducted through the GE Aircraft Engines Chief Engineer's Office.

- **Functionality**

The sensing technique is called birefringence. Continuous wave light at from 790 to 870 nm is transmitted through the sensing element crystal. The result is a spectral pattern of 5 to 6 lobes in the 800 to 870 nm range, the position and width of which are a function of temperature. The optical insertion loss varies from 3 to 10 dB over the operating temperature range.

- **Calibration/Environmental Testing**

The sensor assembly was initially designed to withstand the vibratory and thermal conditions per the F404 engine environment; however, because the sensor was not actually to be engine-mounted during the engine test, environmental testing was waived. Accuracy over the measurement range from -60°F to 340°F and over the EO signal processing circuitry temperature range of from -65°F to 175°F, was tested to be within $\pm 4^\circ\text{F}$.

- **F404 Implementation**

The F404-400 engine uses a single element RTD electrical sensor, de-iced using hot air, mounted through the engine front frame. It was not practical to modify the engine frame for mounting an additional (optical) sensor or to add an optical element to the existing electrical sensor. For an engine ground test, the optical sensor can easily be strapped to the front of the engine support framework. To account for being outside the engine airflow path, the optical sensor signal is adjusted through the EOI software using an estimated recovery factor based on fan speed.

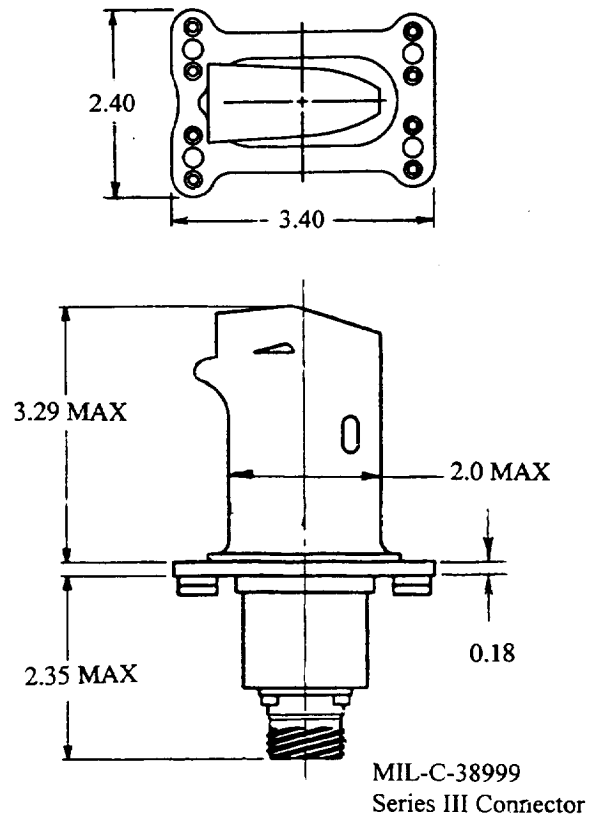


Figure 1 - Typical Optical T1 Temperature Sensor Housing Configuration

3.1.2 Rosemount Design

- **Physical Design Description**

This sensor is identified as Rosemount Aerospace (Burnsville, MN) Model 701J1, the same hardware used on the NASA FOCSI program, transferred for use on this program. A photograph is shown in Appendix A, Figure 29. No additional formal GE design reviews were conducted. Three units were constructed by modifying three Rosemount inlet total temperature sensors, Model 154DR3, chosen on the FOCSI program for its mechanical integrity for use in the engine flow stream and its characteristics similar to the F404 electrical T1 temperature sensor. The electrical connector was replaced with a MIL-C-38999 Series III connector with a single ITT Cannon 200 micron core fiber optic pin contact per MIL-T-29504. The electrical RTD sensing element was replaced with an optical TRD sensing element with a modified mechanical support mechanism.

- **Functionality**

The Rosemount TRD technique is described as follows. Light from a transient source (pulsed or sinusoidal) is transmitted through the optical fiber to the sensing element, consisting of a fluorescent material attached to the end of the fiber. Through absorption, a dopant ion in the fluorescent material is excited to a higher energy state and correspondingly emits a fluorescent signal, at a different wavelength, into the same fiber. With proper material selection, the fluorescent signal can be modeled as an exponential decay with a decay time that exhibits a temperature dependence. The signal processing circuit relates the exponential time constant to a temperature measurement. Being a time based encoding scheme, it is theoretically immune to optical power variations. Average optical insertion loss is 24 dB

- **Calibration/Environmental Testing**

Extensive thermal, vibration, and calibration testing were accomplished by Rosemount under the NASA FOCSI program (ref. 4). The three units were re-tested for accuracy for this program using the Rosemount-designed EO circuit module, from -30 to 75°C (-22 to 167°F) with results within $\pm 1^\circ\text{C}$.

- **F404 Implementation**

This is the same as for the Allied Signal T1 sensor.

3.2 T5 TEMPERATURE PROBE/HARNESS.

3.2.1 Physical Design Description

The T5 probe/harness assembly is identified as Conax Buffalo (Buffalo, NY) Model 2SK-5660. Two assemblies from the NASA FOCSI program, mechanically designed to perform in the F404 thermal, vibration, and gas flow environment, were transferred for use on this program and refurbished. Improvements in the EO signal processing are described in paragraph 4.2.

Each assembly consists of four probes (two long and two short) and an optical cable harness. Each probe assembly consists of a sensing element fabricated at the tip of a sapphire rod, a ceramic support tube for support at the end exposed to combustion gases, and a metal housing with cooling passages over the remaining length. Each probe assembly is joined to the optical cable with a split flange that allows access to the optical components but is not intended to be disassembled in the field. A physical outline of the assembly is shown in Figure 2. A photograph is shown in Appendix A, Figure 30.

A single 200/220 micron optical fiber, with polyimide buffer and additional jacketing, carries the light from each probe, through a transition which groups the four individual fibers into a four fiber bundle, to a special connector which mates with the EO module. The entire harness uses flexible metal outer conduit.

3.2.2 Functionality

The sensing principle for this sensor is blackbody radiation. A source material, embedded at the end of the sapphire light guide, emits radiation varying as a function of temperature. The four probe signals are projected onto a common detector assembly in the EO signal processor, thereby integrating the optical intensity to produce an "optically averaged" signal.

To improve interchangeability over the NASA FOCSI program of both the probe/harness assemblies and the EO circuits, optical properties were more accurately determined by fabricating four new sensing elements, and their performance referenced to a blackbody radiation standard in the calibration furnace.

3.2.3 Calibration/Environmental Testing

Substantial thermal (cycling and soak), humidity, vibration, simulated aerodynamic loading, and calibration testing were accomplished by Conax under the NASA FOCSI program (ref. 4). For this program, the refurbished assemblies were subjected to "burn-in" thermal cycling (room to 500°F) and probe calibration testing over this program's operational temperature range of from 600°F to 1700°F. See paragraph 4.2.3 for results.

3.2.4 F404 Implementation

The F404 engine control system uses two identical four-probed TC harnesses mounted upper and lower on the afterburner case. The four-probed fiber optic harness replaces the lower TC harness, as shown in Figure 13. The engine control signal is thus reduced from an average of eight probes to an average of four probes (electrical or optical). The resulting error due to this configuration is not expected to be significant.

3.2.5 Probe Design Analysis

- **Background**

A design review was conducted through the GE

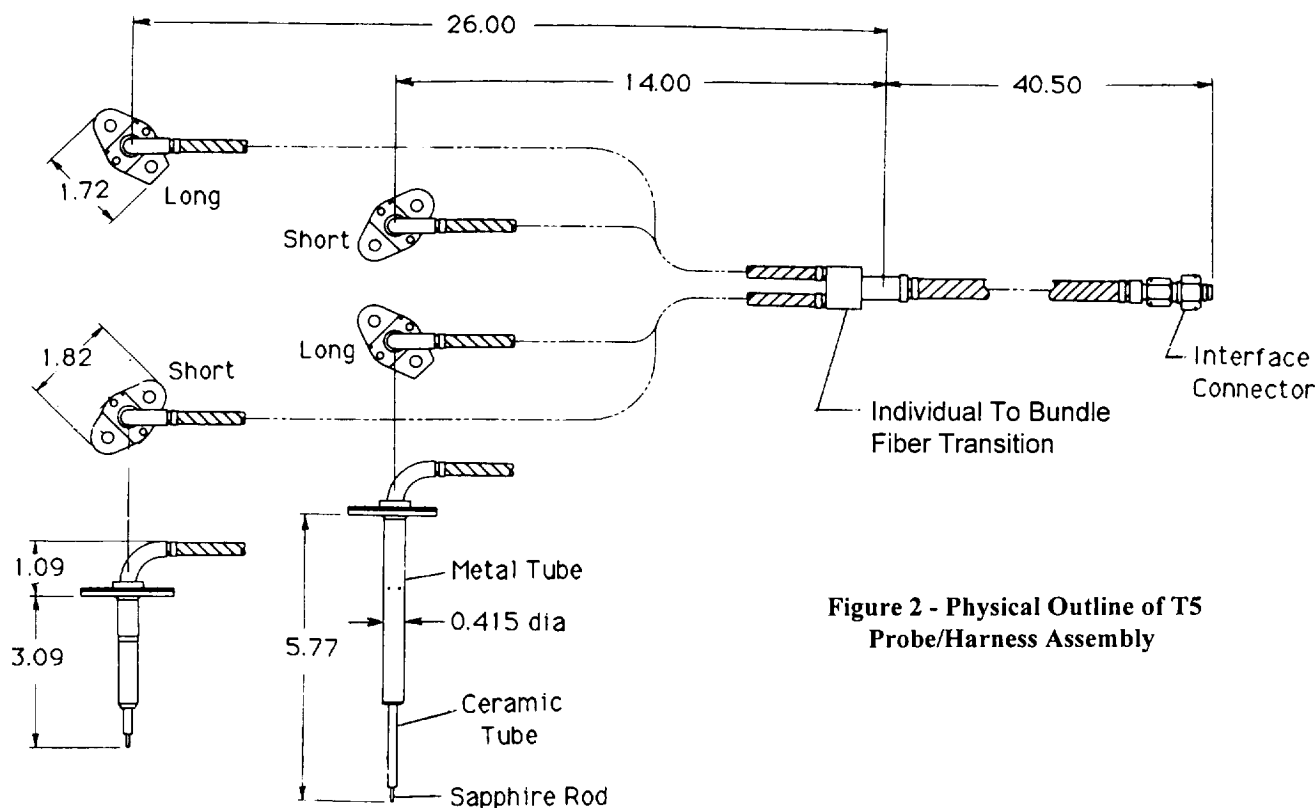


Figure 2 - Physical Outline of T5 Probe/Harness Assembly

Aircraft Engines Chief Engineer's Office to examine the optical T5 probe/harness assembly and its EO circuitry. One issue was the probe failure that occurred during the FOCSI flight test. Inspection of the flight-tested assembly had revealed that the sapphire sensing rod and the ceramic support tube from one of the two long probes was broken off. No data shift was noticed by NASA Dryden over the flight test period presumably because the other three probes provided sufficient signal intensity.

The optical probe assembly was designed to withstand normal F404 engine vibration and aerodynamic loading. Hardware passed significant design assurance testing and completed 250 hours of F404 engine ground testing at GE Lynn in 1992.

- **Analysis Description/Conclusions**

An analysis was performed by Mechanical Analysis Engineering at GE. Conax supplied probe assembly cross sections and material properties. GE constructed an axisymmetric 2-D finite element model to determine vibrational resonances, mode shapes, and stress distributions. The following are conclusions:

1. Under worst case conditions, the stresses in the failed materials appeared to be well below the material

allowable strength limits.

2. Analysis results and previous endurance test and engine test results with other probes of identical design indicate that this one failure event is not related directly to the dynamic environment imposed by the engine.

3. It is suspected that the failed alumina support tube either had a surface or internal defect, undiscovered by Conax inspection, or was subjected to improper handling during installation.

3.2.6 Probe Time Response Testing

- **Purpose**

T5 signal dynamics can affect performance and stability of the engine. The F404 T5 TC junctions are packaged into thin-walled metallic tapered housings. The T5 optical radiating elements are embedded at the tip of a 0.060 inch diameter sapphire rod. Comparing time response characteristics of the TC probes with those of the optical probes was needed in order to determine required software adjustments. Data from the NASA FOCSI engine ground test indicated a difference. Figure 3 shows the time response assumed by the F404 engine model.

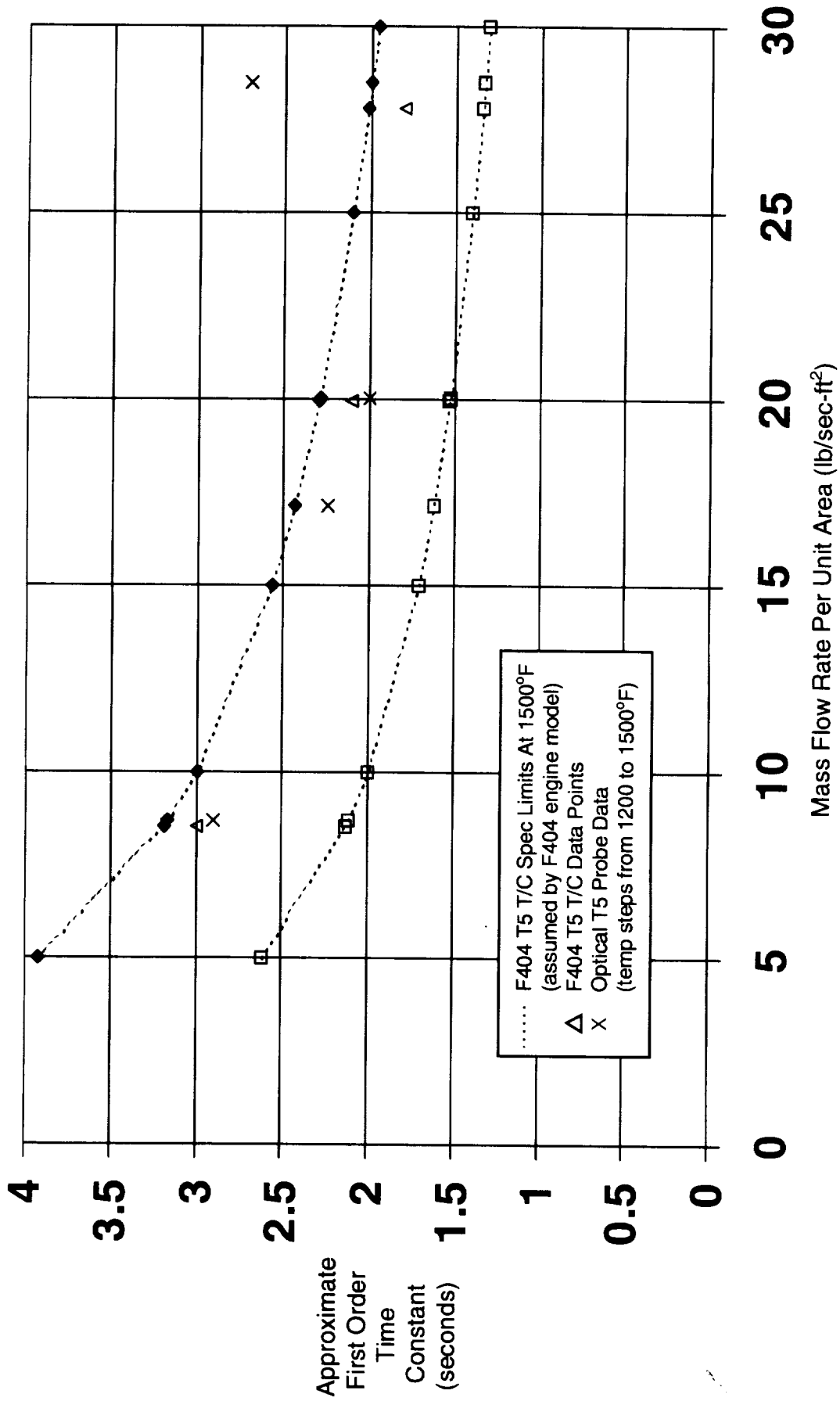


Figure 3 - Results From T5 Sensor Dynamic Response Test

- **Setup/Procedure**

A wind tunnel test was performed at GE Evendale to measure each time response in the same experiment. A F404 TC probe/harness assembly was obtained on loan from GE Edwards. One of the two FOCSI optical probe/harness assemblies and EO circuits coupled with a stand-alone Conax signal processor were provided.

The setup consisted of an eight-inch ID pipe with two reference TC probes and either the four F404 T5 TC probes or the four optical T5 probes installed radially to about the same immersion. A photograph of the setup is shown in Appendix A, Figure 31. Temperature step changes of from 800 to 1000°F, 900 to 1300°F, and 1200 to 1500°F were implemented, each at airflows of 10, 20, and 30 lb/sec-ft². Higher flow conditions were not available.

- **Results**

Initial data using the optical probe/harness was erratic. It was realized that the probes were being exposed to higher than design temperatures. They were designed for a temperature gradient, per F404 specification, of from maximum temperature at the tip to a maximum engine bypass air temperature of about 500°F at the mounting flange. In this test the entire probes were exposed to high temperature. Disassembly and inspection revealed that the internal retention springs were permanently deformed, resulting in a loose interface between the sapphire rod and the fiber cable, preventing proper light transmission. Also, the epoxy-terminated fiber cable tips were damaged. The damaged assembly was sent to Conax for repair.

The test setup was changed to immerse only the probe tips into the airstream, and time response data was obtained using the spare optical probe/harness assembly. At the lower airflow settings the estimated optical probe time response was consistent with the F404 T5 thermocouples (see Figure 3). At the highest airflow level tested (equivalent to part power), the estimated optical probe response was outside of the specification limits of the F404 T5 thermocouple. The time response of the optical probe at high power airflows was unable to be evaluated. See paragraph 7.6.2 regarding implications to the EOI software.

3.3 NL SPEED SENSOR MODULATOR

3.3.1 Physical Design Description

The NL speed sensor modulator is identified as Banks Engineering & Labs Model MOD2010. The FOCSI assembly was redesigned to achieve a smaller insertion loss and a larger ratio of modulation depth to optical DC

noise in the output signal, without the need for an integral electrical transformer. A prototype and two finished assemblies were constructed for this program. Preliminary and critical design reviews were conducted through the GE Aircraft Engines Chief Engineer's Office.

The sensor modulator assembly is packaged to survive demo engine testing. It is encapsulated within a nickel-plated aluminum housing, as shown in Figure 4. The crystal is suspended in RTV inside the modulator assembly which in turn is potted into the housing for resistance to humidity and vibration.

At one end of the assembly, the single input/output fiber pigtail (Brand-Rex OC1260 cable, 100 micron core fiber terminated with a SMA connector, provided by GE) is aligned with the polarizer/lens/retarder/crystal elements. The housing includes outer threads compatible with an ICORE conduit coupling nut to protect the fiber and its interface. At the other end of the assembly is a shielded electrical pigtail, fabricated by Lockheed Martin, Ft. Wayne, IN. The wires originate from the crystal electrodes and interface with a split-off from the F404 electrical NL sensor signal. A photograph of the assembly is shown in Appendix A, Figure 32.

3.3.2 Lithium Niobate Crystal Cut Study

Banks Engineering's design utilizes what is called a Y-axis cut lithium niobate (LiNbO₃) crystal (procured from Crystal Technology) with light propagation along the Z-axis. While Banks Engineering predicted considerable performance improvement over the FOCSI design, investigation by GE Corporate Research & Development, Schenectady, NY, revealed that a Z-axis cut crystal could increase the modulation depth by a factor of 10 and decrease the DC reflection. However, Banks Engineering had evidence to suggest that with Z-axis cut crystals there are periods of amplitude reduction and frequency doubling as temperature changes, so the design was not modified.

3.3.3 Functionality

The sensing element is an electro-optic (Pockels effect) modulator or shutter (ref. 5). The continuous wave input light (810 nm) is collimated, polarized, and passed through the modulator material, which rotates the beam polarization in response to the varying voltage signal, imposed on the modulator through the F404 NL signal at its electrodes. A mirror at the end of the modulator reflects light back through the optical system and is refocused into the fiber. Predicted optical insertion loss is 16 to 18 dB, compared with 34 dB for the FOCSI design.

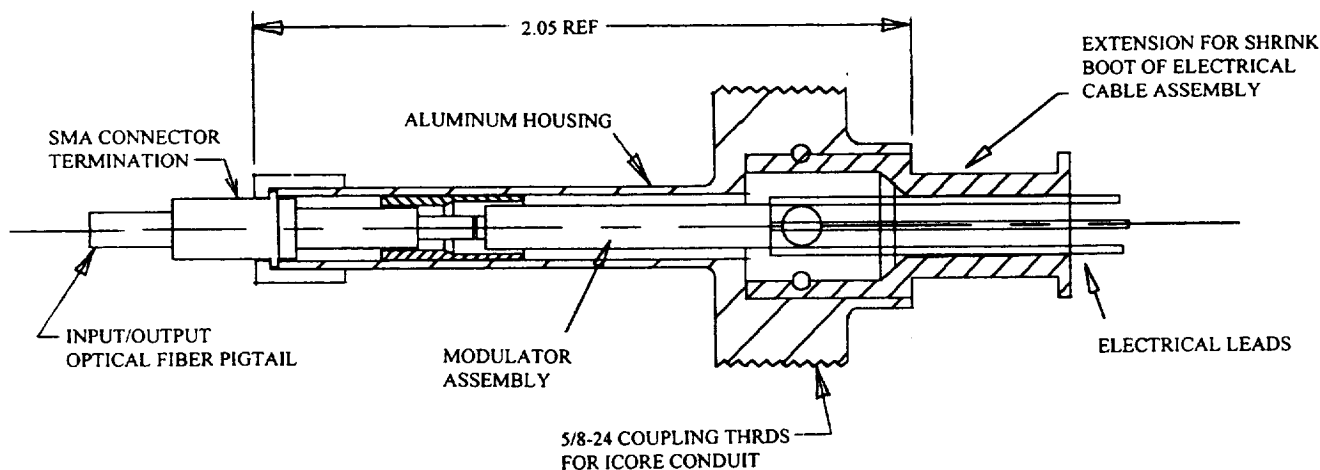


Figure 4 - NL Speed Modulator Assembly

Input voltages from the F404 NL sensor to the modulator crystal are estimated to vary from 1 volt peak-to-peak at 2.8 kHz (one/fan blade frequency at 30% engine speed) to 6 volts peak-to-peak at 10.7 kHz (one/fan blade frequency at 115% engine speed). Since the fan rotor contains 42 blades, the pulse frequency in Hertz at the optical modulator is 0.7 (42/60) times the engine fan rotor speed in RPM. During an engine ground test startup, fan speed is monitored in the control room as speed increases. During the planned engine demonstration of the optical closed-loop control system, the electrical and optical speed signals can be compared.

3.3.4 Calibration/Environmental Testing

The design used under the NASA FOCSI flight test program (ref. 4) was subjected to extensive thermal (cycles and soak), vibration/shock, and humidity testing by Banks Engineering. Because the present program leads only to an engine ground test and because the basic design package for this program is similar, resources were primarily used to improve performance. However, the following reduced environmental testing was performed:

- 10 thermal cycles, 0° to 250°F
- Vibration, 10 to 2000 Hz, 10^7 cycles at resonance

Some vibration induced signal was noted. The plan is to isolate the assembly from vibration during the engine test.

On the FOCSI program, the performance of the processed NL signal was disappointing. For this program, the new design was extensively bench tested with the Allied Signal EO signal processing circuitry during its development

phases with successful results over the specified voltage/frequency range. This is discussed more in paragraph 4.1.3.

3.3.5 F404 Implementation

The F404 engine control system uses two electrical eddy current speed transmitters mounted on the fan frame to count the rotating titanium fan blade tips. The engine will not function properly unless the ECU is receiving two healthy signals. By installing an electrical Y cable, the signal from one electrical speed sensor is split off to the optical modulator, as shown in Figure 17. This is considered the most practical way to produce an optic signal representing fan speed with reliable functionality for demonstration, but a product design would be integrated into a single package.

3.4 NH SPEED SENSOR

3.4.1 Physical Design Description

This sensor is identified as Allied Signal Model FXC-311079, the same hardware used on the NASA FOCSI program, transferred for use on this program. Each sensor uses two 100 micron core fibers for excitation and return light. Its signal interface is a housing mounted MIL-C-38999 Series III connector using Amphenol fiber optic pin contacts per MIL-T-29504/4. The sensing element material limits its temperature capability to 425°F.

Three o-ring grooves on the housing mounting face provide sealing around the probe and two bolts entering

the alternator stator. A dimensional stackup sized the probe length so that there is no chance of interference with the alternator stator. The operating gap is determined to be between 0.020 mils and 0.090 mils and confirmed at each installation. Since the mounting bolts install from inside the alternator stator, the sensor body threaded inserts were carefully reviewed for strength and retention during the FOCSI program. Figure 5 is an outline drawing. A photograph of the assembly is shown in Appendix A, Figure 33.

3.4.2 Functionality

This is categorized as a Magneto-Optic of Faraday effect sensor. The input light (730 nm) is passed through a linear polarizer, a magneto-optic crystal, and a cross-polarizer. As the magnetic field in the alternator fluctuates, the intensity of the transmitted light is modulated since the magneto-optic crystal rotates the light polarization. The probe design permits minimum light through in the unexcited state. The amount of light modulation decreases as temperature increases, but is unaffected by rotor speed. Average measured optical insertion loss is 28 dB, with a modulation depth of from 5 to 15 dB.

The alternator rotor has 9 magnetic poles. The engine gearbox to engine core speed ratio is 1.59091. Therefore the pulse frequency output from the sensor in Hertz is 0.239 X engine core speed in RPM.

3.4.3 Calibration/Environmental Testing

Extensive thermal (cycles and soak), vibration/shock, and humidity testing were accomplished by Allied Signal under the NASA FOCSI program (ref. 4). The units were functionally re-tested for this program at Allied Signal using the Allied Signal-designed EO circuit module.

3.4.4 F404 Implementation

The F404 engine control system includes a gearbox-mounted electrical alternator which provides a NH speed signal by using the output from a separate winding. The optical speed sensor probe is mounted onto and through a modified alternator stator (see photograph in Appendix A, Figure 34) as shown in Figure 6, and is modulated by the magnetic poles of the alternator rotor.

3.5 FVG POSITION SENSOR

3.5.1 Physical Design Description

This sensor is identified as Litton Poly-Scientific Model FO3575-1, the same hardware used on the NASA FOCSI program, transferred for use on this program, and repaired. No additional formal GE design reviews were conducted. Three units were originally constructed.

This is a linear position sensor with a ± 1.35 inch optical stroke and 0.25 inches mechanical over-travel at each end. The rod end turnbuckle has ± 0.050 inches of adjustment. Each sensor uses two 100 micron core fibers for excitation and signal light. Its optical interface is a MIL-C-38999 Series III connector using Amphenol fiber optic pin contacts per MIL-T-29504/4. Its mechanical interface for engine mounting is a flanged/slotted clamp around the circular (1.00 inch diameter) outer body. Figure 7 is an outline drawing. A photograph is shown in Appendix A, Figure 35.

3.5.2 Functionality

This sensor uses digital wavelength division multiplexing. The sensor is excited by a 750 to 900 nm source spectrum through the input fiber. After passing through a coupler, a grin lens, prism, and grating are used to spread the light across the code plate. Reflected light is collected and returned through the output fiber to the EO circuitry. The optical insertion loss is 14 to 26 dB.

The sensor shaft is a 12 bit-encoded linearly moving scale. With 1024 discrete positions over 2.7 inches, the resolution is 0.0026 inches.

3.5.3 F404 Implementation

The F404 engine control system uses a single electrical LVDT position sensor mounted inside the FVG actuator. The optical position sensor is mounted parallel with and external to the FVG actuator. At this location, the optical sensor is not subjected to fluid immersion. Photographs of the installation are shown in Appendix A, Figures 36 and 37.

3.5.4 Environmental/Calibration Testing

Substantial thermal (cycling and soak), humidity, vibration/shock, and extend/retract endurance testing were accomplished by Litton Poly-Scientific under the NASA FOCSI program (ref. 4). One of the original three units was considered expended after this testing. Of the remaining two units, one was used by Allied Signal for development of the EO signal processing, the other sent to Cybernetic Research Laboratories (CRL), Tucson, AZ to set

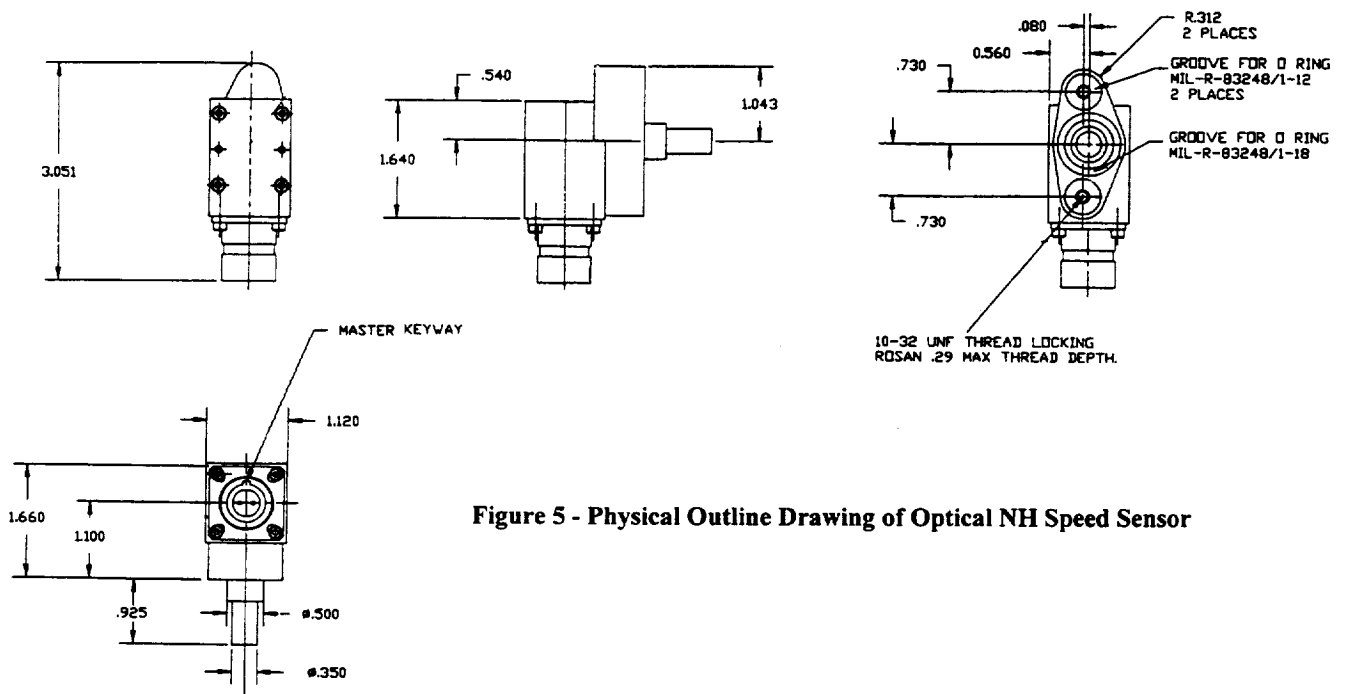


Figure 5 - Physical Outline Drawing of Optical NH Speed Sensor

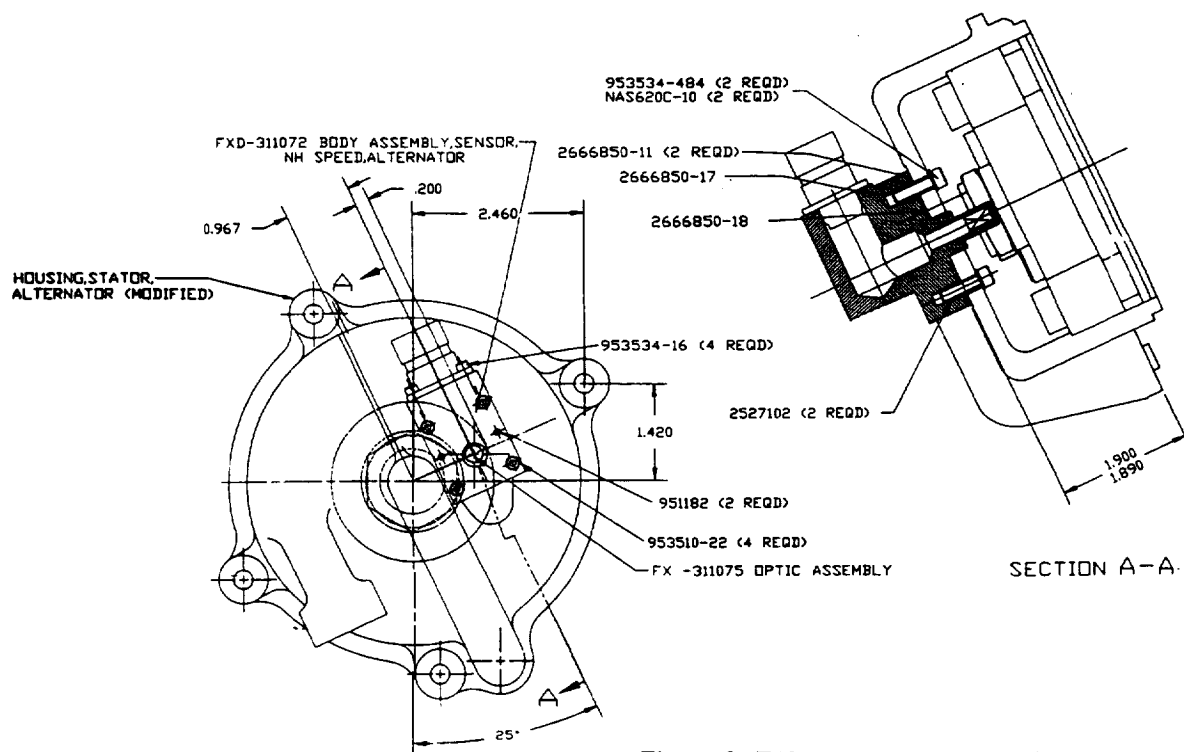


Figure 6 - F404 Alternator Layout Showing Installation of Optical NH Speed Sensor

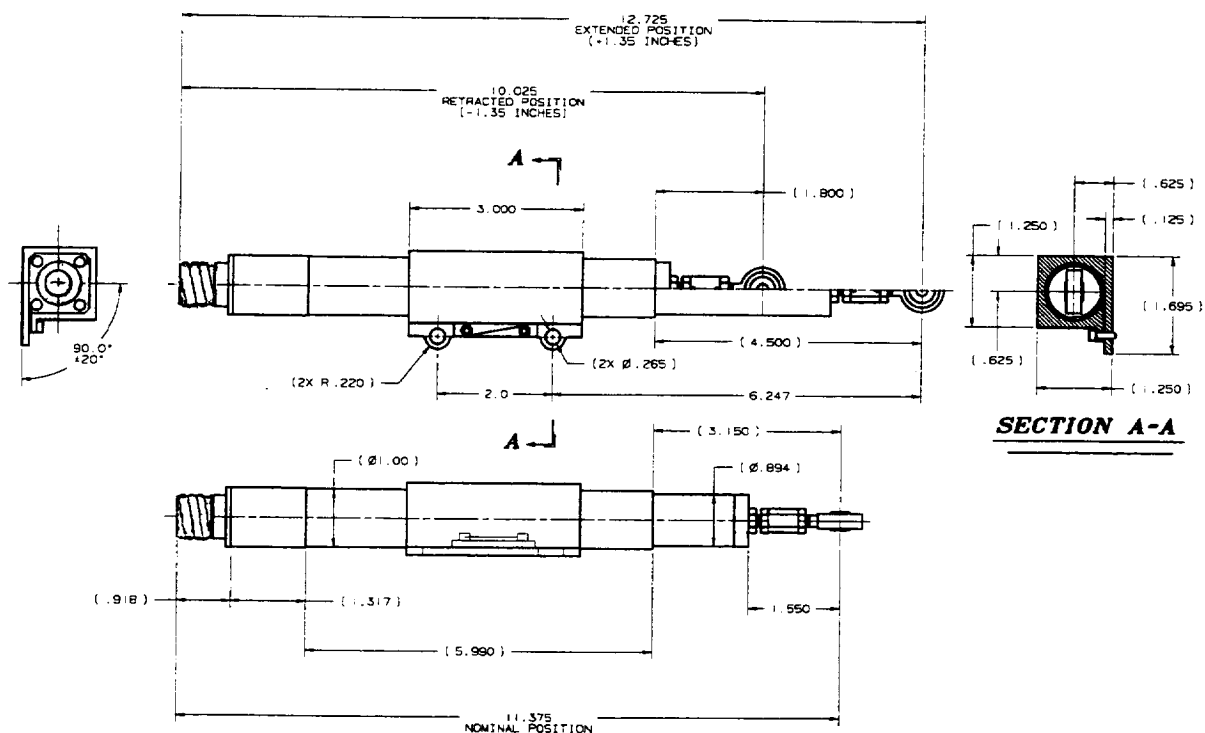


Figure 7 - Outline Drawing of Optical FVG Position Sensor

up for testing.

Testing was done at CRL in order to confirm accuracy performance and to determine dynamic characteristics. For this testing, EO signal conditioning circuitry was borrowed from Allied Signal. Room temperature static calibration testing of the two FVG sensors demonstrated accuracies of $\pm 0.3\%$ full scale for S/N 002 and $\pm 0.15\%$ full scale for S/N 003. This is acceptable performance for use in the F404 engine control system.

3.5.5 Dynamic Testing At CRL

Slew rate and sinusoidal response testing were performed at CRL to confirm acceptability of the sensor/circuitry design for closed-loop position control on the F404 engine. The F404 FVG system requires an actuation velocity of at least 2.16 inches/second for sea level operation. The setup included using optical FVG sensor S/N 003 and a motorized controller with reference position measurement, as shown in the photograph in Appendix A, Figure 38.

The *slew rate test* procedure consisted of triangular wave drive cycles with about a 1.2 inch peak to peak

stroke centered near the total stroke midpoint, beginning at velocities of 0.5 inches/second and increasing in increments of 0.5 inches/second to 3.0 inches/second, collecting 1875 data samples per cycle.

The *sinusoidal cycling test* procedure consisted of sinusoidal wave drive cycles with about a 0.3 inches peak to peak stroke centered near the total stroke midpoint, beginning at 1.0 Hz and increasing in increments of 1.0 Hz to 5.0 Hz, collecting 1000 samples per cycle. This corresponded to a maximum velocity of 4.78 inches/second at 5.0 Hz.

The FVG subsystem exhibited essentially close to unity gain out to 5 Hz. The measured phase shifts roughly reflected the expected 5 millisecond digital update delay (see paragraph 7.5), without additional first order effects. No optical data smearing was observed (see paragraph 4.1.7).

3.5.6 Repairs At Litton

During dynamic testing at CRL (see paragraph 3.5.5), one of the two functional FOCSI sensors experienced internal mechanical failure. This unit and the unit expended

during FOCSI testing were sent to Litton with the goal of providing one good refurbished unit out of the two, as a spare for this program. Upon inspection, Litton reported that both units had broken fibers between the external connector and the optical coupler.

This sensor's input/output fibers are easily broken by

retracting or extending the rod too far or by twisting the rod. For the one repaired unit, Litton spliced in new input/output fibers, cleaned accessible optical surfaces, and inspected and tested the light path. Following repair, the unit was sent to Allied Signal where proper functionality using their EO processing circuitry was confirmed.

4.0 ELECTRO-OPTICS CIRCUITRY

4.1 ALLIED SIGNAL EO CIRCUITRY

4.1.1 Physical Design Description

This module is identified as Allied Signal P/N 1502701. Two assemblies were fabricated for this program. They are capable of operation at temperatures up to 85°C. The component area is about 7.0 x 4.4 x 1.08 inches. GE requested the heat sink framework area be increased to 8.0 x 6.43 inches to conform to the size of the other three EOI card cage modules. Lockheed Martin provided a Hypertronics card edge connector for the 31 power and data wires and Calmark card slot locking retainers. Seven 100 micron jacketed pigtail optic fibers communicate with the four optical sensors described below. Photographs of the two sides of the module are shown in Appendix A, Figures 39 and 40.

4.1.2 Functionality

This module provides optical power and signal processing for the following optical sensors: the Banks NL speed sensor modulator, the Allied NH speed sensor, the Litton-Poly-Scientific FVG position sensor, and Allied T1 temperature sensor. It outputs a 16 bit binary code to the Lockheed Martin comparison/validation circuitry. The first 11 bits are sensor data, the remaining 5 bits represent data identifiers and status. It also outputs TTL pulses representing the optical NL/NH signals.

The sensor converted digital data are stored in four registers and accessed by three memory address bits. The first two registers are always used for the FVG measurement because the engine control system requires a faster data update rate from FVG than for the other signals. The remaining two registers are used to store T1, NL, or NH data. The data are fetched in groups of two: FVG/T1, FVG/NL, or FVG/NH. The data type stored in the register corresponds to the frame count, repeated every three minor frames.

Data word formats are as follows:

T1: (0 to 2048) represents (-65°F to 350°F)
FVG: (0 to 1024) represents (0 to 2.7 inches)
NL: (0 to 2048) represents (1,500 to 11,500 Hz)
NH: (0 to 2048) represents (150 to 4,500 Hz)

The Allied EO circuitry uses +5 VDC and ±15 VDC at a combined maximum power of 12 watts. The assembly includes a platinum element RTD (500 ohms at 0°C)

mounted to monitor board surface temperature.

4.1.3 Optical Signal Characteristics

• T1 Temperature

The excitation output to the sensor is a continuous wave from a 790 to 870 nm LED with half power width of about 80 nm. Power coupled into the fiber is in the range of -9 to -3 dBm (126 to 501 microwatts). The return signal input is a 5 to 6 lobed spectral pattern in the 800 to 870 nm range.

• NH Speed

The excitation output to the sensor is a continuous wave at a wavelength of 730 ± 20 nm center wavelength spectrum at a power of -8 to -1 dBm (160 to 795 microwatts). The return signal input is a quasi-sinusoidal waveshape at frequencies from 195 to 4425 Hz, with a modulation depth from 5 to 15 dB.

• NL Speed

In order to improve engine test performance of the NL speed measurement, the Allied EO circuit for this application incorporates increased excitation output level and improved circuit shielding compared with the EO circuit used for the FOCSI program. More discussion on noise effects is given in paragraph 4.1.6. EO circuits were provided to Banks Engineering to use during development of the new NL speed sensor modulators.

The excitation output to the modulator is a continuous wave from a 840 ± 20 nm LED (ABB HAFO, Inc. P/N 1A288 SMA-2A, suggested by Banks Engineering) entering one leg of a 2X1 splitter, at a power of from -6 to -3 dBm (251 to 501 microwatts). The return signal input is a quasi-sinusoidal waveshape with a predicted modulation depth of from 0.43 dB at 2,787 Hz (30% speed) to at least 3.05 dB at 11,147 Hz (120% speed), and a DC reflected power of up to 1.5% of the excitation power received at the modulator.

• FVG Position

A customized CCD WDM optic receiver assembly was fabricated to meet the wavelength requirements of this sensor. The excitation output to the sensor is a continuous wave resulting from combining output from a 790 to 870 nm LED with half-power width of about 80 nm, with output from a 780 nm LED with half-power width of about

30 nm. The combined power coupled into the fiber is in the range of from -11 to -5 dBm (79 to 316 microwatts). The return signal input is a binary encoded pattern of 11 data bits producing 1024 uniquely resolvable positions over the 2.7 inch stroke. The modulated wavelengths are primarily in the range of 770 to 880 nm.

4.1.4 Calibration/Environmental Testing

Testing at Allied Signal included verifying acceptable optic source power to each sensor and confirming signal conditioning performance to worst-case operational limits (optic power loss) of the system (ref. 6). Acceptable accuracy at several operating points in the range of each sensor signal interface (FVG/T1/NL/NH) was confirmed with the EO module at -65°F, room, and 175°F. For example, FVG position errors were within ± 0.005 inches. Environmental testing (vibration/shock and thermal cycling) was not performed because the EOI assembly will not be engine mounted during the planned test.

4.1.5 NL Signal Phase Shift

There is a F404 control system requirement to not exceed a maximum phase shift between the two NL signals received by the ECU. Having the optical NL signal be useable therefore requires that it not only be compared in frequency with a normal electrical sensor signal and validated, but that it also be sent straight through the EOI as an analog signal to maintain its phase relationship, instead of being reconstructed from its digital value. More discussion on this topic is contained in paragraph 7.7.3.

4.1.6 Effects of Optical NL Signal Noise

The optical NL modulator described in paragraph 3.3 uses one fiber communication, which simplifies connectorization but interface back-reflections cause a decreased signal-to-noise ratio. The optical signal from the modulator passes through an optical coupler and enters the receiver circuit consisting of a photodiode detector, two gain stages, and a comparator for zero crossing detection and conversion into a TTL square wave. The zero crossing detection includes a tripping voltage hysteresis level to prevent multiple zero crossings due to the noise. However, the resulting TTL wave contains jitter in the position of the 0 to 5V transition.

The TTL signal then takes two paths:

1. Destination: Digital Word For Use In Validating the Optical Measurement - The signal is counted over a

precise time base of 9 milliseconds using a special speed measurement integrated circuit. This provides averaging of 16 pulses (increasing with speed) at the low end of the speed range.

2. Destination: EOI Analog Output To the ECU - The TTL signal with time jitter feeds into the Lockheed Martin circuitry to convert it into a ± 5 Vpp signal for output to the ECU. The jitter should not affect ECU processing except that it results in effective phase shift (see issues discussed in paragraph 4.1.5). Fortunately, at low speeds where jitter due to noise is larger, the phase shift due to filtering is small, and at high speeds, where phase shift due to filtering is large, jitter due to noise should be negligible.

4.1.7 FVG Position Sensor Signal Processing

A minimum FVG slew rate requirement of 2.16 inches per second (see paragraph 7.6.1) corresponds to a maximum optical FVG signal processing time of 1.22 milliseconds per bit, to prevent a condition known as signal "smearing".

$$2.7 \text{ inches} / 1024 \text{ bits} = .0026367 \text{ inches/bit} \\ (.0026367 \text{ in/bit}) / (2.16 \text{ in/sec}) = 1.22 \text{ milliseconds/bit}$$

Allied Signal reported that signal processing is accomplished in times on the order of 1 millisecond or less depending on which S/N position sensor was under test. The absence of smearing at required slew rates was demonstrated from testing at CRL (see paragraph 3.5.5).

4.2 CONAX EO CIRCUITRY

4.2.1 Physical Design Description

This EO circuit assembly is identified as Conax Model 318149-001. Two units were fabricated for this program, incorporating the main circuit board design and using machined piecepart hardware from the EO assemblies used on the NASA FOCSI program, transferred for use on this program. It is a dual board assembly measuring 0.7 x 2.0 x 4.0 inches, incorporating a special optical connector to mate with the end of the 4-probed harness. Its 21 electrical lead wires were connectorized by Lockheed Martin to mate with an AirBorn connector on the motherboard. A photograph of the module is shown in Appendix A, Figure 41.

Besides improved hardware interchangeability (discussed in paragraph 3.2.2), this program also provided elimination of the 5 watt thermo-electric cooler (used on FOCSI to maintain circuit temperatures below 55°C in environments up to 90°C), and an extension of the low end

of the measurement range. The EO circuitry was revised to allow the photodetector to operate to 95°C (203°F), without the thermoelectric cooler.

4.2.2 Functionality

This module processes the optical T5 probe signals and outputs a 12 bit binary code representing the T5 measurement to Lockheed Martin comparison/validation circuitry. At temperatures below 600°F, the output value is 0; at temperatures above 1800°F, the output is 4095. Between 600°F and 1200°F, the output is 1°F per bit, for example, 610°F has a binary value of 610. From 600°F to 1200°F (low range), the measurement is based only on the output from an Indium-Gallium-Arsenide detector in the spectral band from 1000 to 1800 nm. This represents a lower limit extension of the operating range from the FOCSI program in order to achieve operability over the full range of engine idle conditions. From 1200°F to 1800°F (high range), the measurement is based on the ratio of the output of the Indium-Gallium-Arsenide detector with the output from a silicon detector in the spectral band from 400 to 1000 nm. In the upper range, being a ratio mode, the measurement is more accurate than in the lower range.

The Conax EO circuitry uses +5 VDC and ±15 VDC at a combined maximum power of 2.5 watts. The output includes two built-in test bits. A processor status bit reflects routines evaluating RAM, ROM, and input/output operations throughout the normal program execution. An optical harness status bit indicates optical signal path condition, which can be checked when the system is operating in the ratio mode. The asynchronous parallel electrical interface allows the temperature value to be read whenever required.

4.2.3 Calibration/Environmental Testing

Substantial thermal (cycling and soak) and vibration testing were accomplished by Conax under the NASA FOCSI program (ref. 4). For this program, the new EO module design was subjected to 30 thermal cycles (-65°F to 203°F) and calibration testing over this program's operational probe temperature range of from 600°F to 1700°F. Vibration was deleted because the EOI will not be engine mounted.

The probe/harness assemblies and EO modules were calibrated together and the errors compared to the program's system allowances of ±25°F for high range probe temperatures, and ±50°F for low range probe temperatures. (A study during the FOCSI program showed that the F404 T5 thermocouples meet a total system error of ±18°F.) For

the two probe/harness/EO sets evaluated, one set exhibited relatively low errors of about ±10°F and ±30°F, respectively, over the upper/lower probe temperature ranges and over the -65°F to 203°F EO circuitry environment, and the other set exhibited errors of about ±20°F and ±50°F, respectively. The first set is the prime test set for the planned engine test.

Interchanging the probe/harness assemblies and EO circuits produced a small effect on calibration for the prime EO circuit but a significant calibration effect (out of limits) for the other EO circuit.

4.3 ROSEMOUNT EO CIRCUITRY

4.3.1 Physical Design Description

This module is identified as Rosemount P/N 105E7958G1. One assembly was provided for this program. It is capable of operation at temperatures up to 85°C. The circuitry component volume is about 7.0 x 3.4 x 1.05 inches, surrounded by an aluminum flange, but the area was increased to 8.0 x 6.43 inches for this program in order to fit into an over-sized SEM-E card slot. Lockheed Martin provided a heat sink frame on which the board was bonded. This provides integration with the EOI card cage and more mechanical integrity and thermal dissipation than Rosemount's original frame. Lockheed Martin also provided Hypertronics card edge connector for the 27 power and data wires and Calmark card slot locking retainers. One 200 micron jacketed pigtail optic fiber communicates with the Rosemount T1 optical sensor. Photographs of the two sides of the module are shown in Appendix A, Figures 42 and 43.

4.3.2 Functionality

This module provides optical power and signal processing for a Rosemount optical T1 sensor and outputs a 12 bit binary code representing its measurement to Lockheed Martin comparison/validation circuitry. A bit value of 0 represents -30°C; a bit value of 4094 represents 200°C. Additionally there are three data transfer control bits and two status bits. The circuitry uses +5 VDC and ±15 VDC at a combined maximum power of 4 watts.

4.3.3 Optical Signal Characteristics

The excitation output to the sensor is a square wave pulse train at frequencies from 25kHz to 50kHz depending on the temperature of the probe. The "on" state power is about 75 microwatts. The wavelength is broadband,

centered at 660 nm, with a full width half max of approximately 50 nm.

The return signal input from the sensor is at 50% duty cycle. The first half of the duty cycle is a signal with increasing amplitude with an inverse exponential shape. That is, the amplitude increases quickly at first and levels off, coming to a constant level if the frequency is low enough. The second half of the duty cycle is a signal with exponentially decaying amplitude, starting from the final value of the increasing signal in the first half of the duty cycle. The wavelength is approximately 710 to 790 nm.

4.4 INTERFACE CONTROL DOCUMENTS

Interface control documents were prepared by GE for the Allied Signal, Conax, and Rosemount EO circuit modules. These were reviewed and signed by Lockheed Martin and each EO circuit designer, but not issued as formal GE documents. They describe and provide concurrence on:

- electrical power requirements
- electrical connector interface configuration
- digital data word formats
- data signal status characteristics (built-in-test)
- data output transfer control procedures
- optical fiber configuration, and
- optical signal characteristics

5.0 ELECTRO-OPTICS INTERFACE ASSEMBLY

5.1 PHYSICAL DESIGN

5.1.1 Chassis Design

Initially there was a chance that this program could lead to a flight demonstration. Therefore, the external configuration of the environmentally tested FOCSI EOU, designed for installation on the F404 engine during F18 flight testing, was adopted for this program's EOI, maintaining capability for use of fuel-cooling, but with the internal configuration re-designed. Two chassis were procured by Lockheed Martin from George Industries, Endicott, NY, a production chassis manufacturer. Photographs of the chassis with connectors installed are shown in Appendix A, Figures 44 and 45.

5.1.2 Card Cage and Motherboard

There are four 8.0 x 6.43 inch boards (over-sized SEM-E's) mounted in the card cage: the Allied Signal EO module, the Rosemount EO circuit module, the Lockheed Martin analog board, and the Lockheed Martin digital board. Each includes an electrical board connector to interface power and signals with the Lockheed Martin motherboard. Figure 8 shows views of the card cage shown broken out from the chassis. The 14-layered motherboard integrates the Allied Signal, Conax, and Rosemount EO modules and the Lockheed Martin analog module with the Lockheed Martin digital module.

5.1.3 Power Supply

Input power to the EOI is 28 VDC. The power supply board has flying leads terminated with a connector to plug into the EOI motherboard. It supplies +5 VDC and ± 15 VDC. Maximum power usage is about 65 watts. The board is approximately 4.2 x 11 inches in size.

5.2 FUNCTIONALITY

5.2.1 Block Diagrams

Figures 9 and 10 show two versions of a system functional schematic of the EOI. The shaded blocks represent the signal conditioning for the six fiber optic sensors provided by Allied Signal, Conax, and Rosemount resulting in digital output to the validation software. All other circuitry was designed and provided by Lockheed Martin Control Systems, Johnson City, NY.

Analog signal conditioning and A/D circuitry convert the five normal F404 sensor signals into digital format. Digital circuitry logic determines the validity of the fiber optic sensors compared with the normal sensors. D/A circuitry and analog signal conditioning converts the fiber optic measurements into signals compatible with the F404 ECU control. Signal selection logic either passes the normal sensors straight through or permits the converted fiber optic signals to be transmitted to the ECU for engine control.

5.2.2 Signal Flow Structure

The processing path of the analog and optical sensor signals through the EOI share a general signal flow structure for all of the sensed engine parameters. A typical signal flow diagram is shown in Figure 11. The electrical/optical signals for each of the sensed engine parameters are converted from their original signal formats to a digital signal. The digital signals are filtered and dynamically compensated to represent the normal input signals for the F404 ECU. The signals are then range checked and limited to the expected signal range. The optical signals are then converted from the digital signal to the ECU expected analog signal format for the sensed parameter. A more detailed description of the software is presented in Section 8.0. The switched analog output signals to the ECU are based upon:

- (1) the validity status of the optical signal,
- (2) the health status of the EOI, and
- (3) optical/analog signal selection commands received through a remote MIL-STD-1553B terminal.

5.3 CIRCUIT MODULES

5.3.1 EO Modules

The Allied Signal and Rosemount EO modules mount in the EOI assembly card cage and interface through Hypertronics card edge connectors with the Lockheed Martin motherboard. The Allied EO module includes seven 100 micron core optical fiber pigtails terminated with Amphenol pin contacts per MIL-T-29504/4, which insert into chassis wall connector receptacles. The Rosemount EO module includes one 200 micron core optical fiber pigtail.

The Conax EO module mounts in the EOI chassis as a stand-alone unit with 21 electrical power/data leads terminated by an Airborn connector mating with a connector on the Lockheed Martin motherboard.

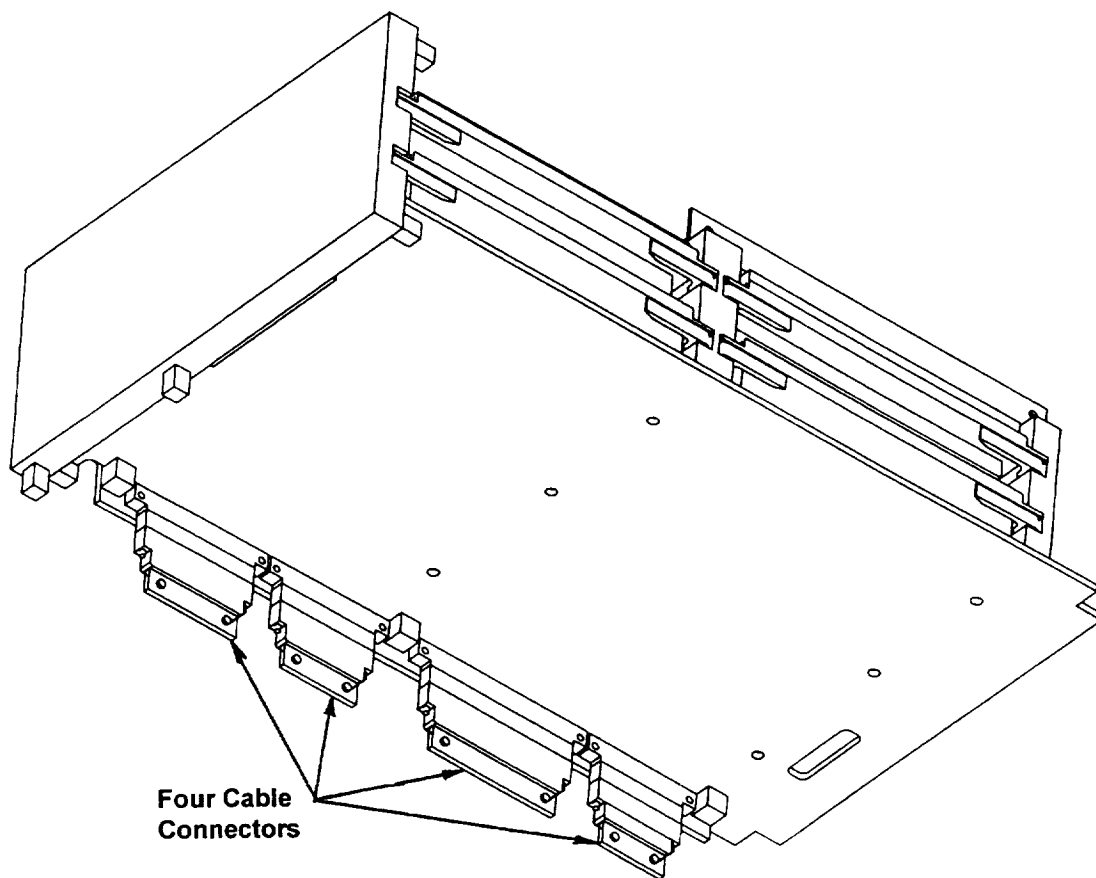
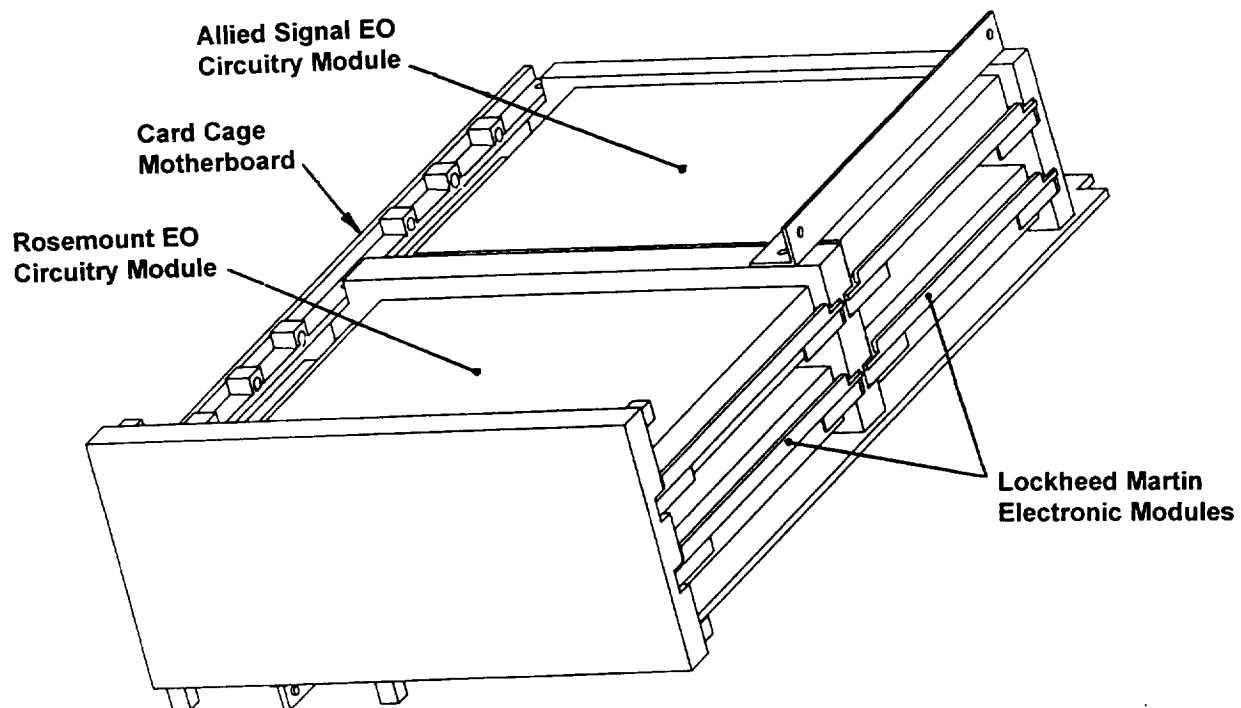


Figure 8 - Views of the EOI Card Cage

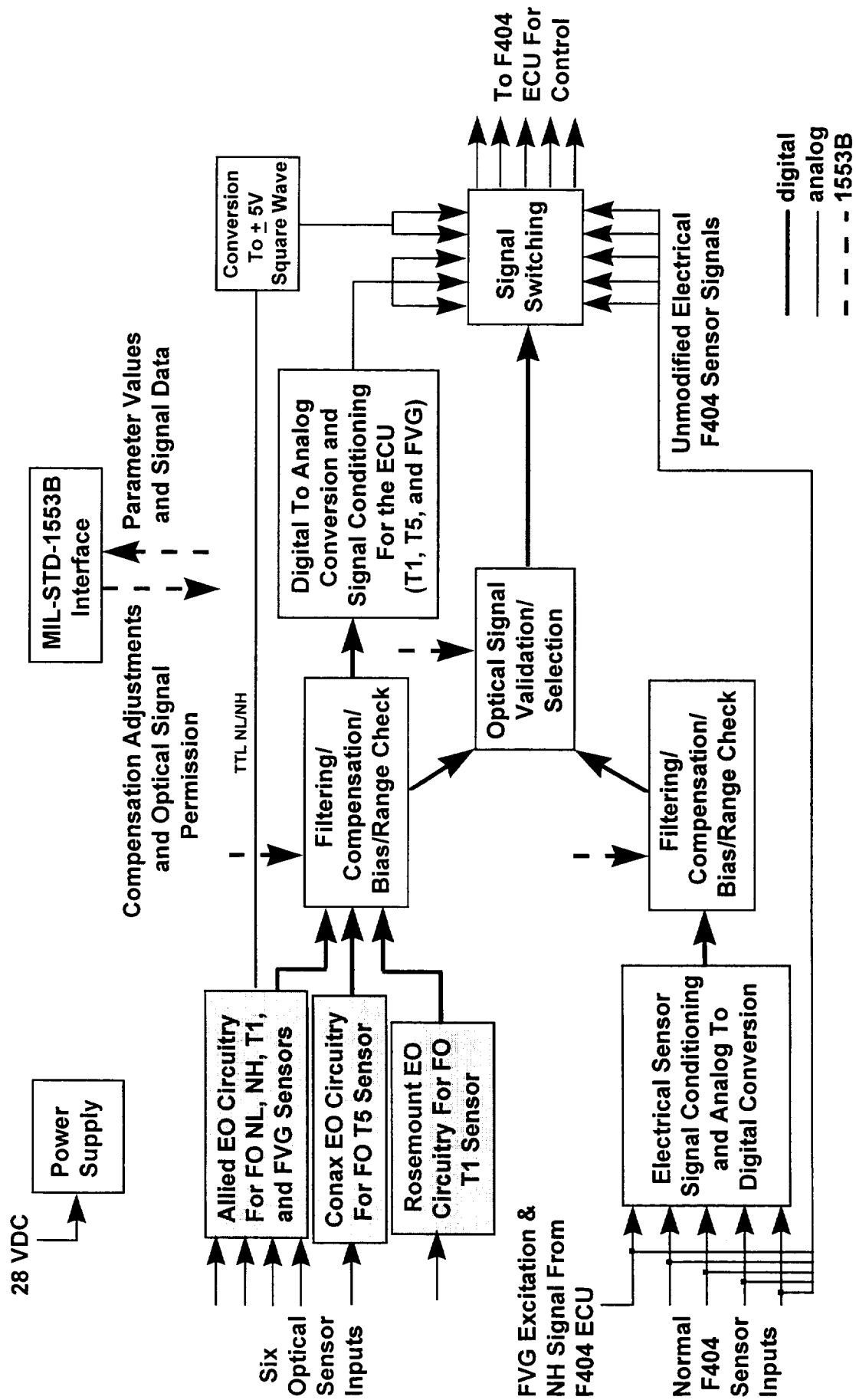


Figure 9 - EOI System Functional Schematic

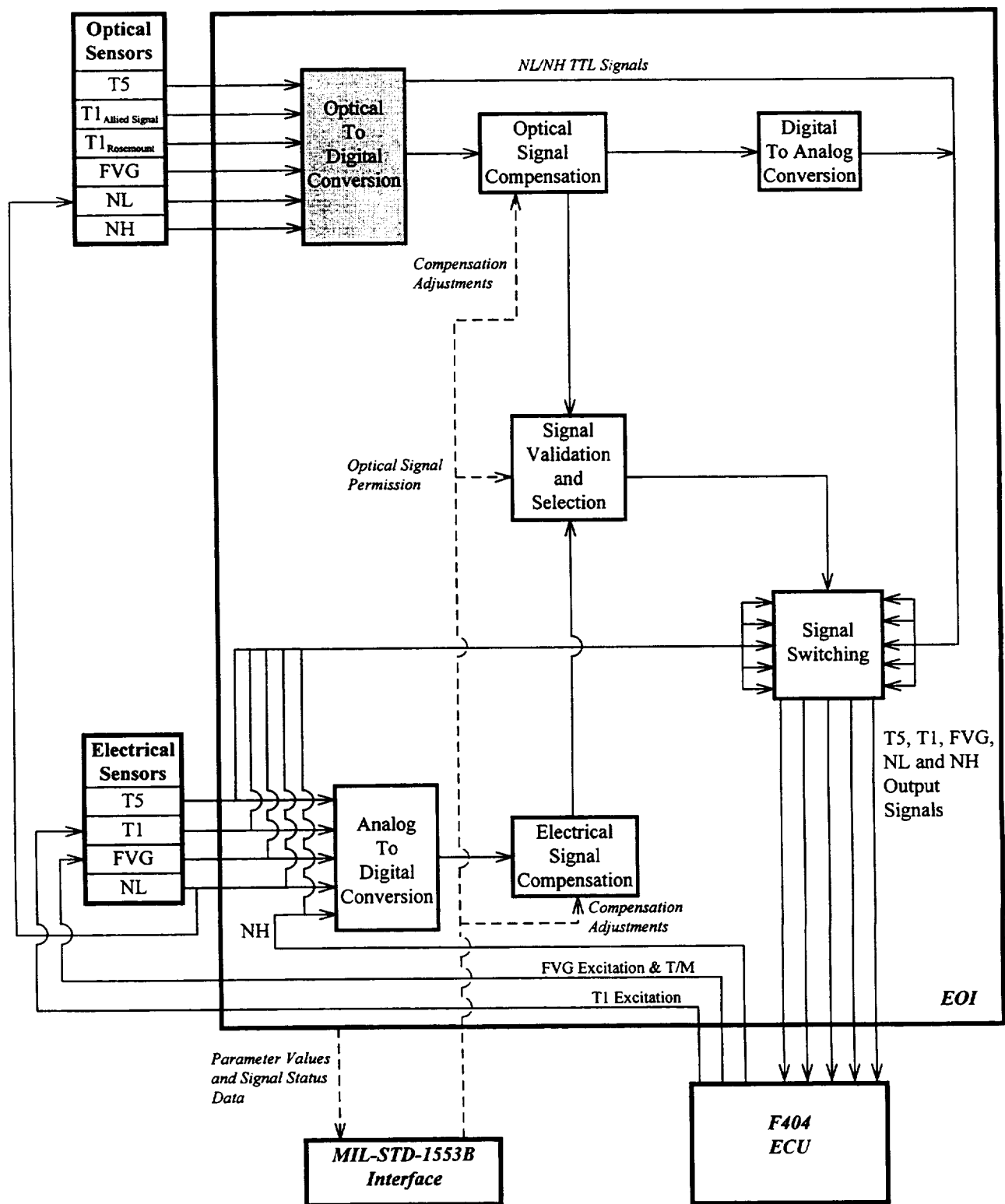


Figure 10 - EOI System Functional Schematic

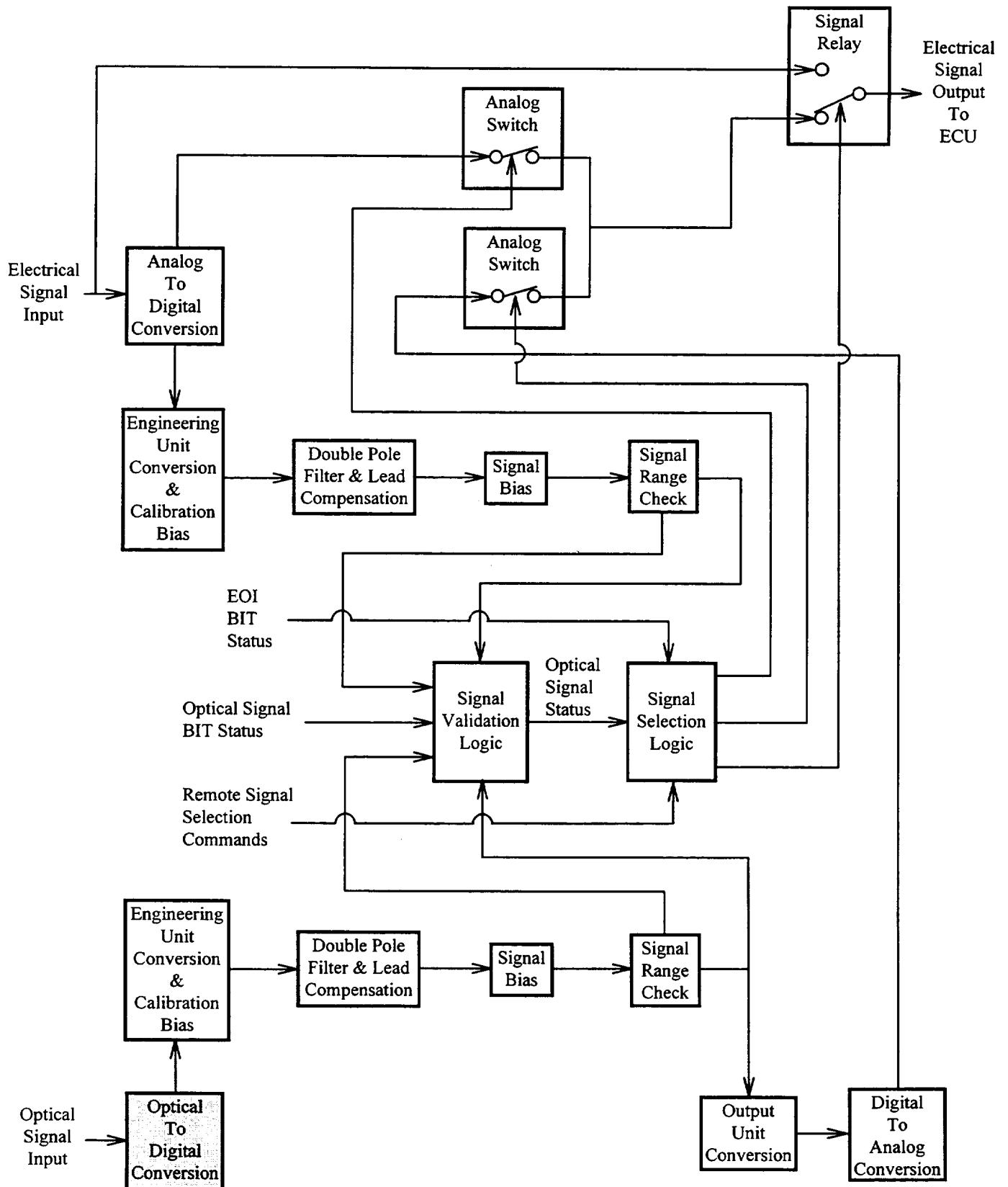


Figure 11 - Typical EOI Signal Flow Structure

5.3.2 Analog/Digital Circuit Modules

This circuitry is designed/fabricated by Lockheed Martin, Johnson City, NY. It provides signal processing for the normal F404 engine electrical NL/NH/T1/T5/FVG sensor signals, receives the six processed optical sensor signals, performs the required compensation, comparison, and validation, and outputs the chosen signals through MIL-STD-1553B data and in proper analog format to the F404 ECU.

The circuitry consists of an analog module and a digital module, each the size of an over-sized 8.0 x 6.43 inch SEM-E card, capable of environmental temperatures up to 125°C. A photograph of both sides of each module is shown in Appendix A, Figures 46 and 47. Both modules mount in the EOI assembly card cage and interface through Hypertronics card edge connectors with the Lockheed Martin motherboard

5.4 INPUTS/OUTPUTS

The EOI receives input signals from three sources: sensor signals, a MIL-STD-1553B data bus, and a RS-232 serial interface. Figure 12 indicates the function of each chassis connector interface. Internal signals are also generated to monitor EOI health (Allied EO module temperature) and to compensate T5 thermocouple signals (T5 cold junction temperature). Figures 13 through 17 describe the pathways of the optical and electrical signals from their respective sensor inputs to the EOI, to permitted EOI analog outputs transmitted to the ECU.

5.4.1 F404 Analog Input Sensor Signals

Five normal F404 analog sensor signals are input to the EOI to help determine validity of the optical sensor signals. They would normally input directly with the ECU. In the normal control system mode (see paragraph 7.1), the signals pass directly through the EOI to maintain normal engine operation.

The analog T1 and FVG sensor signal inputs come from their respective single electrical engine sensors. The analog NL sensor signal input comes from one of the two electrical engine sensors, the same one which energizes the optical NL sensor modulator. The analog T5 sensor signal comes from the remaining of two (one replaced by the optical probe/harness) four-probed thermocouple harness (actually four separate signals).

NH speed is electrically sensed through a separate winding in the engine alternator. It was not considered

prudent to interfere with the interconnections between the alternator (providing control system power) and the ECU. Therefore for this demonstration, it was decided to break out an analog signal representing NH speed from within the ECU.

5.4.2 Optical Sensor Input Signals

Six optical sensor signals are input to the EOI. Optical T1, FVG, NL, and NH signals are processed by the Allied Signal EO module. An optical T5 signal is processed by the Conax EO module. Another optical T1 signal is processed by the Rosemount EO module. These are described in more detail in Section 4.0.

5.4.3 MIL-STD-1553B Data Bus Signals

- **Receives**

The EOI queries the MIL-STD-1553B RAM every 5 milliseconds and reads any subaddress received. Input signals include simulated analog or optical sensor signals for verification testing of the EOI system as well as the setting of EOI adjustments (min/max limits, adders, scalars, and time constants). Bit packed words are configured to enable the simulated sensor signals, choose between use of the Allied Signal or Rosemount optical T1 signals, disable a faulty BIT function, override optical signal validation requirements, perform EOI reset operation, and permit selection of the optical sensor signals.

- **Transmits**

Output signals provide information relative to the operation of the EOI as well as the engine system. They are read into MIL-STD-1553B RAM every 15 milliseconds. These include data representing each normal F404 sensor measurement and each optical sensor measurement at various stages through the signal processing logic, max/min limits, calibration adjustments, and the Allied Signal board temperature. Bit packed words are configured to identify the status of faults, overrides, permissions, optical signal validities, the positions of switches (open/closed) and relays (analog/optical), and the source of the EOI outputs (analog/optical).

5.4.4 RS-232 Interface

This is used to interrogate the status of internal EOI signals and for input of EOI adjustment and signal selection parameters.

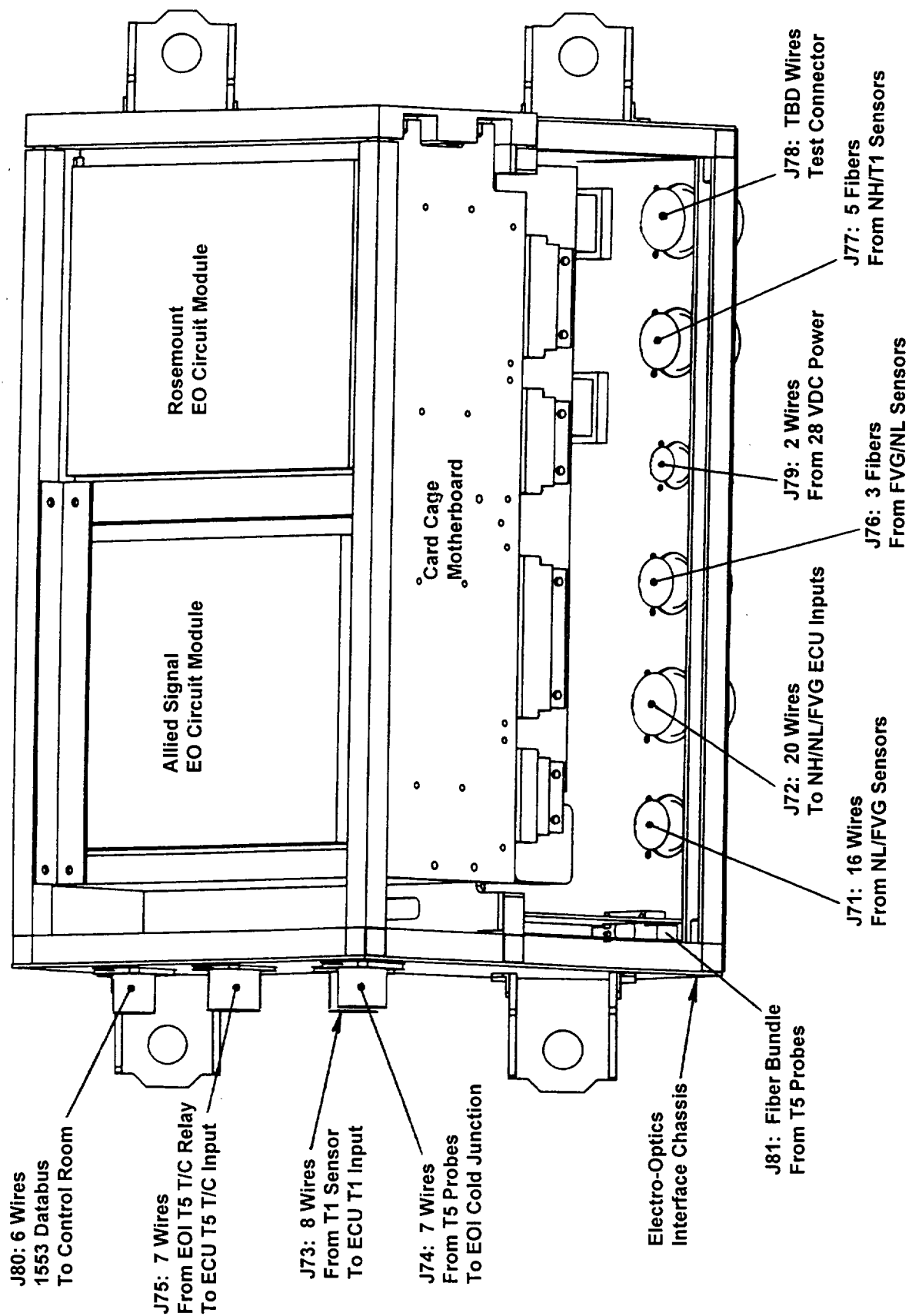


Figure 12 - Function of Each EOI Chassis Connector Interface

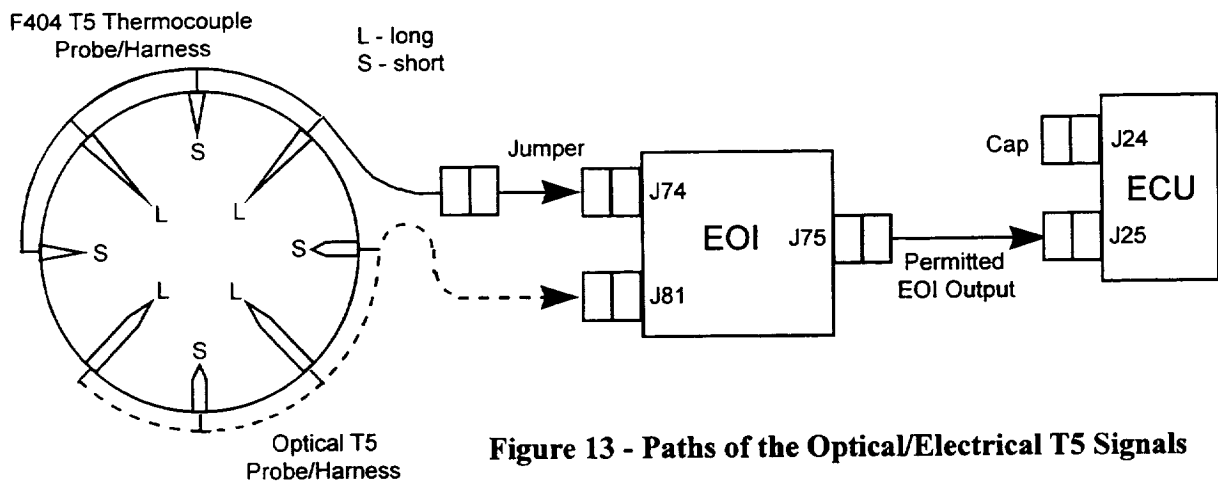


Figure 13 - Paths of the Optical/Electrical T5 Signals

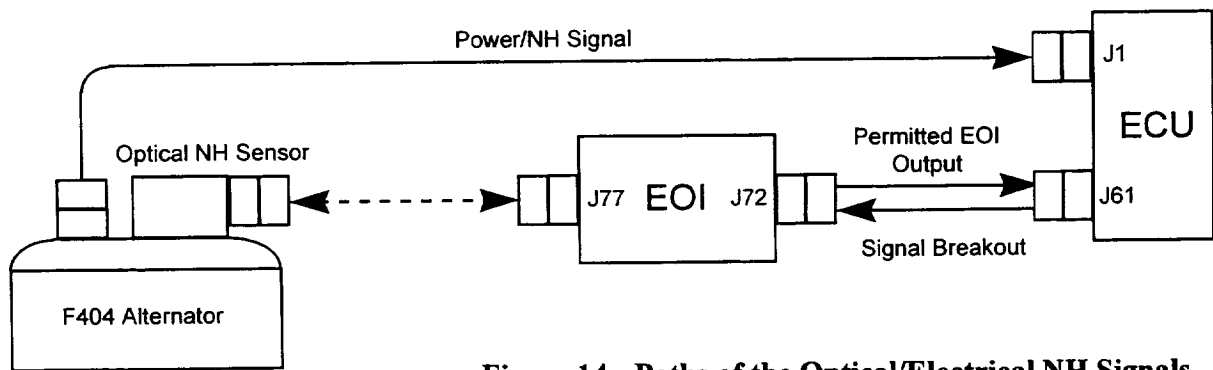


Figure 14 - Paths of the Optical/Electrical NH Signals

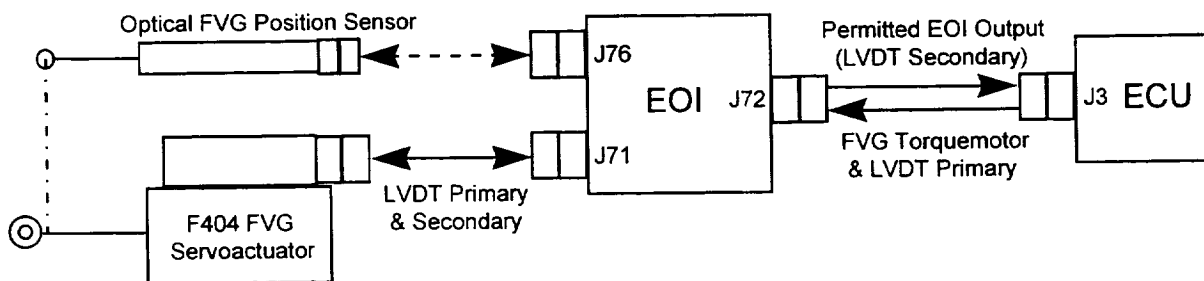
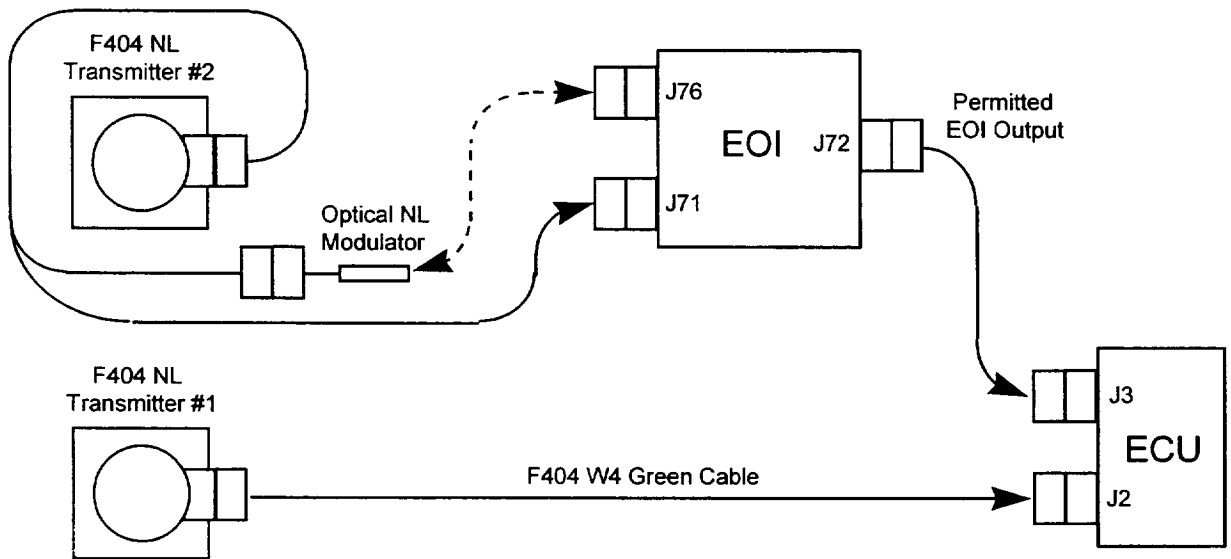
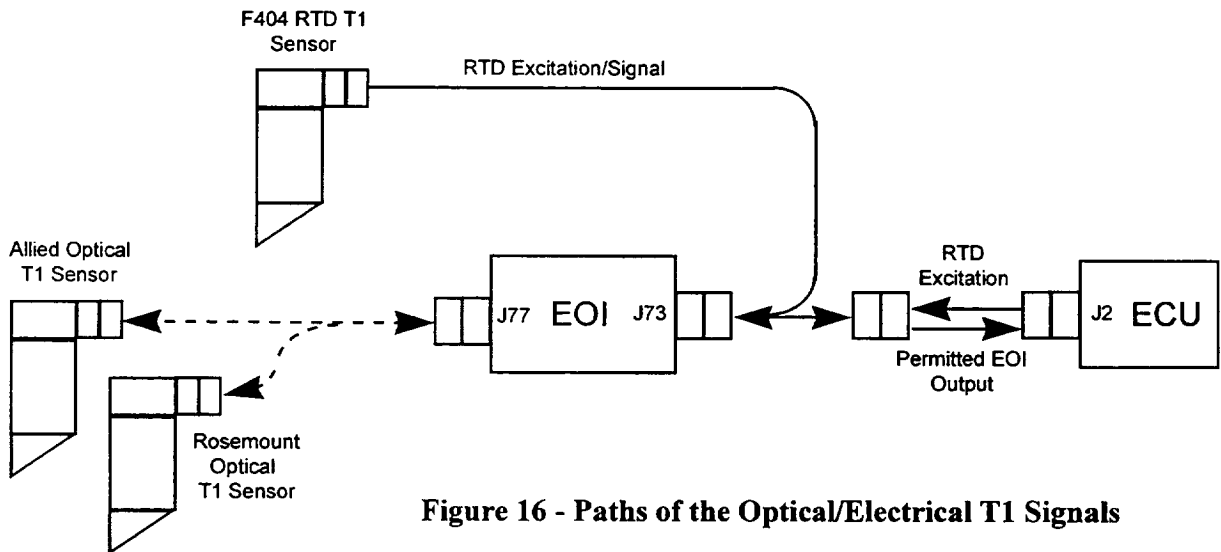


Figure 15 - Paths of the Optical/Electrical FVG Signals



5.4.5 Output Signals To The ECU

The EOI output to the F404 ECU input interface consists of five sensed parameters (T1, T5, FVG, NL, and NH). Their source is selected between the five normal F404 sensor inputs to the EOI and the six optical sensor inputs to the EOI. The EOI output of all of the normal F404 sensor inputs and the optical NL and NH sensor inputs are not modified by the EOI signal processing logic. However, the normal F404 sensor inputs are also utilized in the validation of the optical sensor signal inputs to the EOI.

The normal F404 sensor inputs are provided to the ECU in their original analog format while the optical NL and NH signals are provided directly from the Allied Signal EO module as TTL signals (0 to 5V) but modified to $\pm 5V$ signals for output to the ECU. The optical T1, T5, and FVG sensor signals are compensated by the EOI signal processing and converted to analog signals.

5.5 ASSEMBLY & BENCH/ENVIRONMENTAL TESTING

Two functional EOI assemblies (except for the EO modules) were completed by Lockheed Martin, Johnson

City, NY, including installation and functional checkout of the motherboard, power supply, TC cold junction, analog module, and digital module, and installation and wiring to the chassis interface connectors. Installation of the EO modules was performed by GE. Photographs of the assembly are shown in Appendix A, Figures 48 through 51.

The EOI assembly design for this program is very similar to the assembly used for the NASA FOCSI program, which was vibration and engine tested. Lockheed Martin guided the internal EOI design based on production design practices. No additional vibration testing was conducted because the assembly will not be mounted on the engine during the planned engine ground test.

Integration testing of an assembled EOI by Lockheed Martin was first performed without software to check out the basic analog input/output signal flows and component functionalities over the anticipated engine ground testing temperature range of 30°F to 120°F. With a full software build installed, room temperature testing was completed to confirm that analog input signals over their operating voltage ranges are received and processed correctly. After installation of the EO modules, the EOI assembly is ready for detailed hardware/software integration testing and the planned acceptance testing as described in Section 9.0.

6.0 CABLES/INTERCONNECTIONS

6.1 EOI INTERCONNECTIONS

Figure 18 is a general diagram showing interconnections between the sensors, EOI, and ECU. Figure 19 shows an overall interconnection schematic including some of the pathways inside the EOI. Figures 20 and 21 show details of the conductors and connector pins. More details of the engine cables are described in Section 11.0.

6.2 ELECTRICAL CABLES

The new electrical engine cables, similar in design to production engine cables, were fabricated by Lockheed Martin at Ft. Wayne, IN. The normal F404 cable configuration is modified to reroute the electrical T1, T5, NL, NH, and FVG signals to the EOI, and then from the EOI to the ECU. One of the standard F404 engine cables is replaced by a new cable, and there will be five additional electrical engine cables, plus the EOI power and MIL-STD-1553B cables running into the control room. Photographs of the electrical cables are shown in Appendix A, Figures 52 through 55.

6.3 FIBER OPTIC CABLES

Figure 22 shows how the fiber optic sensors are interconnected with the EO circuitry in the EOI.

6.3.1 GE-Designed Fiber Optic Cables

These are used to connect all of the fiber optic sensors to the EOI except T5. For the Allied T1/NH sensors, the Banks NL modulator, and the Litton FVG sensor, Brand-Rex fiber optic cable style OC-1260, purchased from Colonial Wire & Cable, Leominster, MA, is used. This is a 100/140 micron core/cladding glass fiber with 0.29 NA, polyimide-coated and semi-loose within a thin-wall

fluoropolymer tube, surrounded by a braided, teflon-coated fiber-glass strength member, covered by a teflon FEP 0.083 inch OD outer jacket all rated from -65°C to 200°C. For the Rosemount T1 sensor, Brand-Rex cable style OC-1283, 200/220 micron core/cladding with 0.22 NA and the same type packaging, is used.

The ends of the fiber cables are terminated with MIL-T-29504/5 socket contacts per Amphenol Aerospace design. The 100/140 micron core terminations were performed by Amphenol Aerospace using parts kits supplied by GE, including Epo-tek 353ND optical epoxy, purchased from Amp, Inc., Harrisburg, PA. Rosemount terminated the 200/220 micron core fiber cable for their sensor. The contacts install into the size 16 electrical cavity of a MIL-C-38999 Series III electrical connector using standard electrical contact insertion tools.

The fiber optic cable assemblies for the engine test were completed at GE Evendale. The fiber cable is housed within flexible, crush resistant conduit, fabricated by ICORE International, Sunnyvale, CA, also providing bend radius control. The thermally-stabilized inner PTFE conduit is available with inside diameters ranging from 0.188 to 0.625 inches, chosen to fit the number of optical conductors. The conduit is wrapped with a reinforcing wire to add crush/kink resistance, covered with a non-metallic outer braid, and crimped to end fittings which thread to the MIL-C-38999 connectors. Multiple branches are formed by assembling sections of conduit using wye or double wye transition fittings. Photographs of the two fiber optic assemblies are shown in Appendix A, Figures 56 and 57. Note that the EOI/J77 cable includes a 90° connector backshell fitting to relieve a tight fit at engine assembly noticed on the NASA FOCSI program.

6.3.2 T5 Temperature Probe Harness

This is described in paragraph 3.2.1.

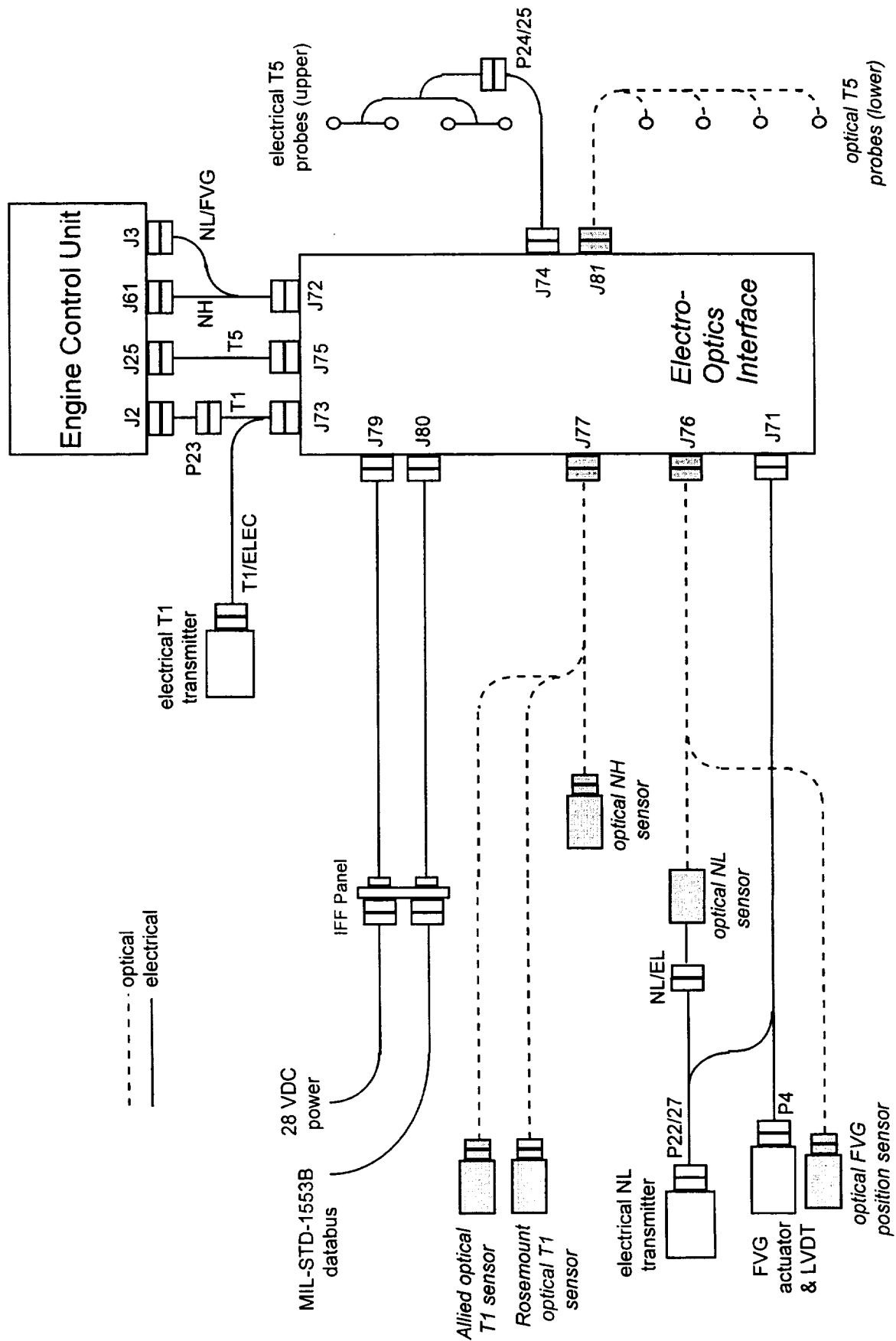


Figure 18 - General Sensor/EOI/ECU Interconnections

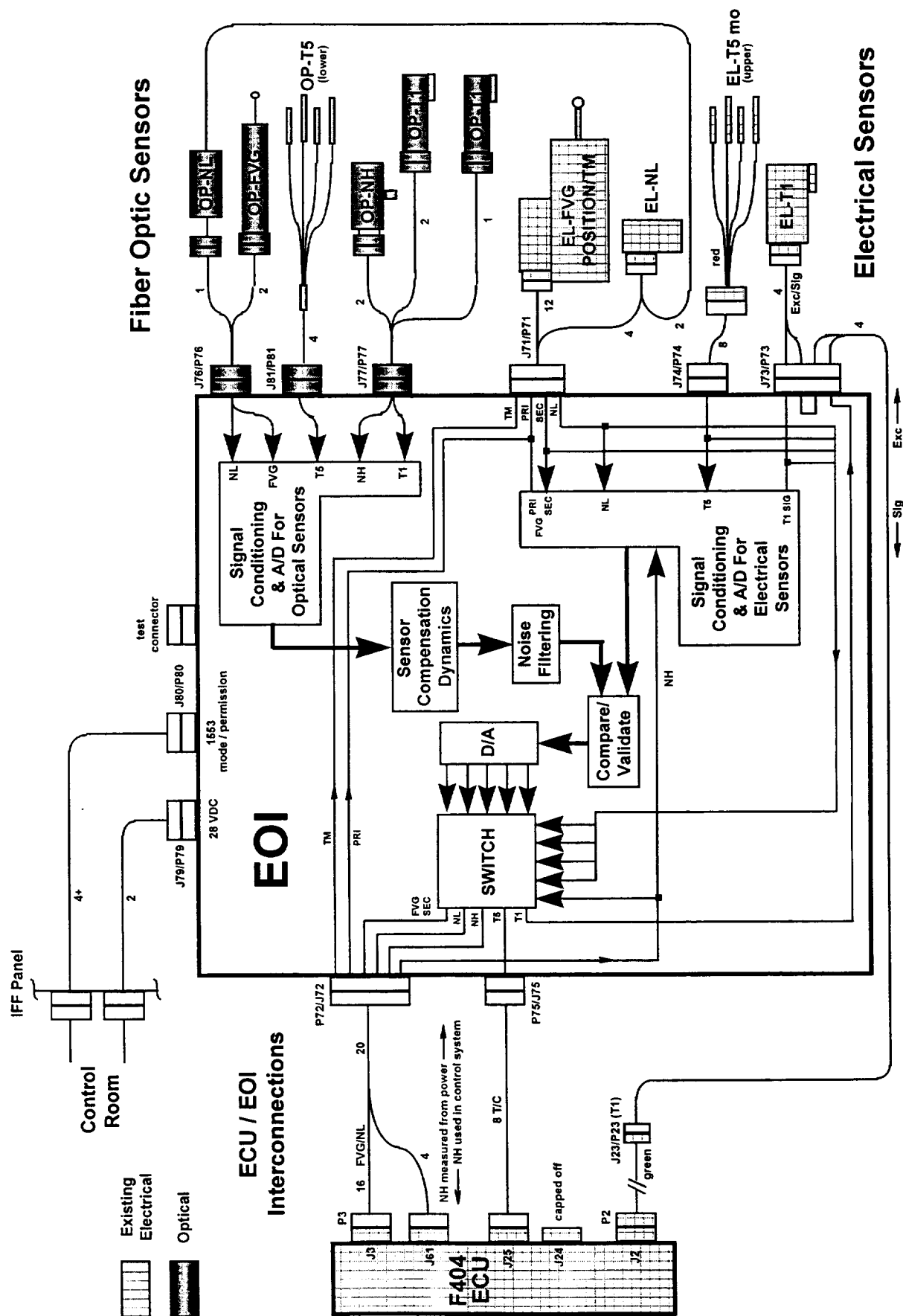


Figure 19 - EOI Internal/External Interconnection Schematic

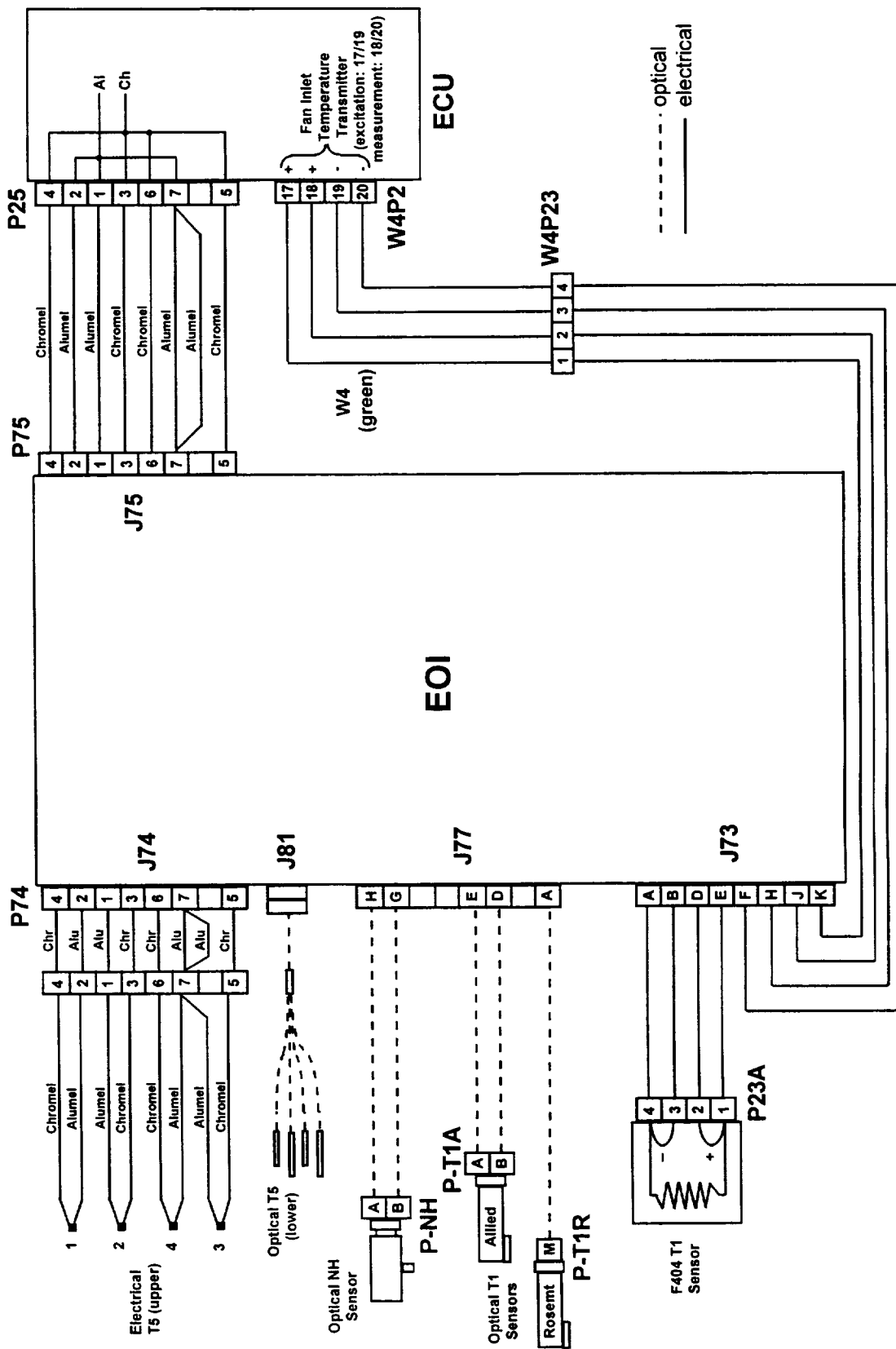


Figure 20 - Interconnection Schematic I Showing Connector Pin Details

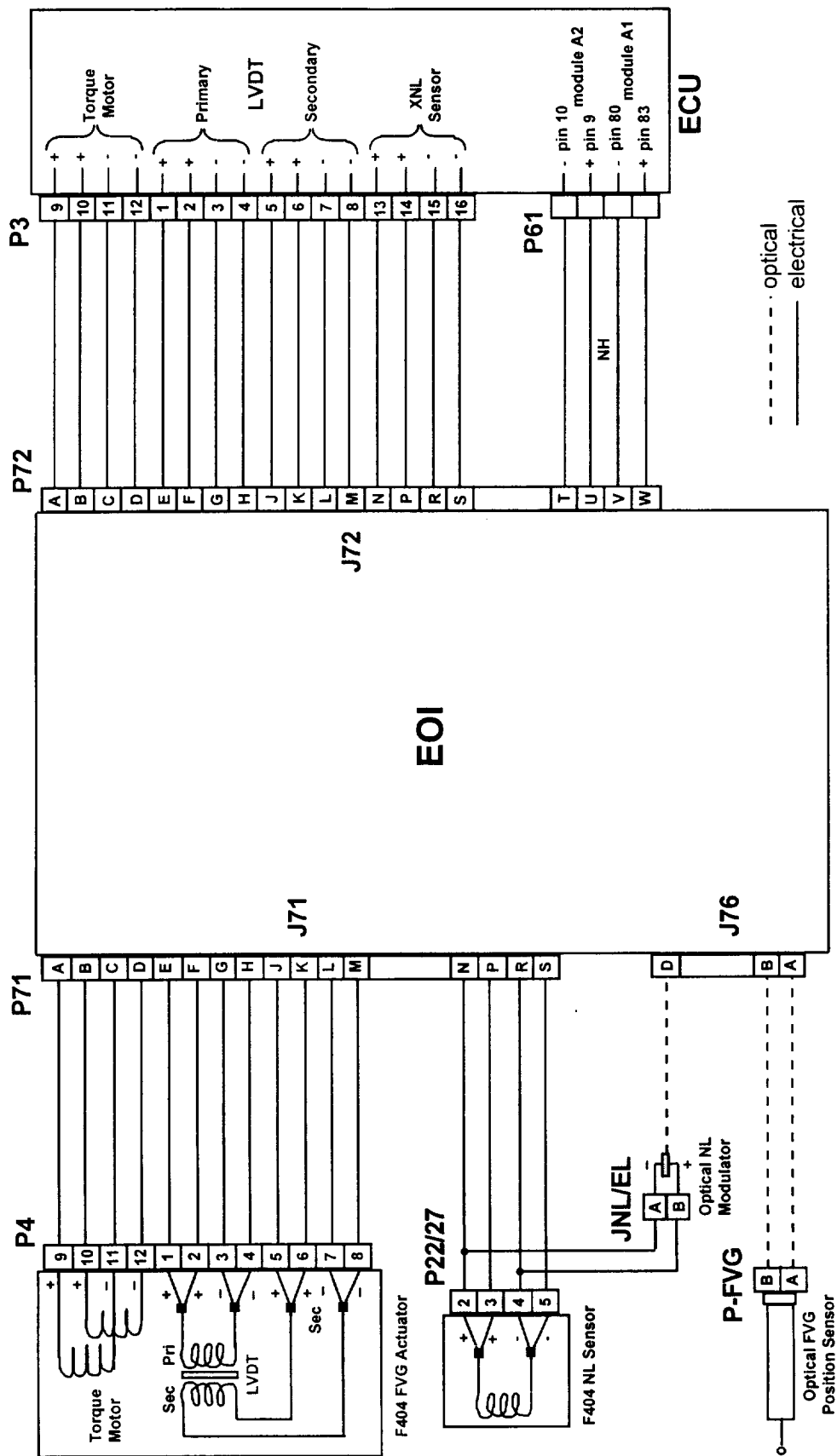


Figure 21 - Interconnection Schematic II Showing Connector Pin Details

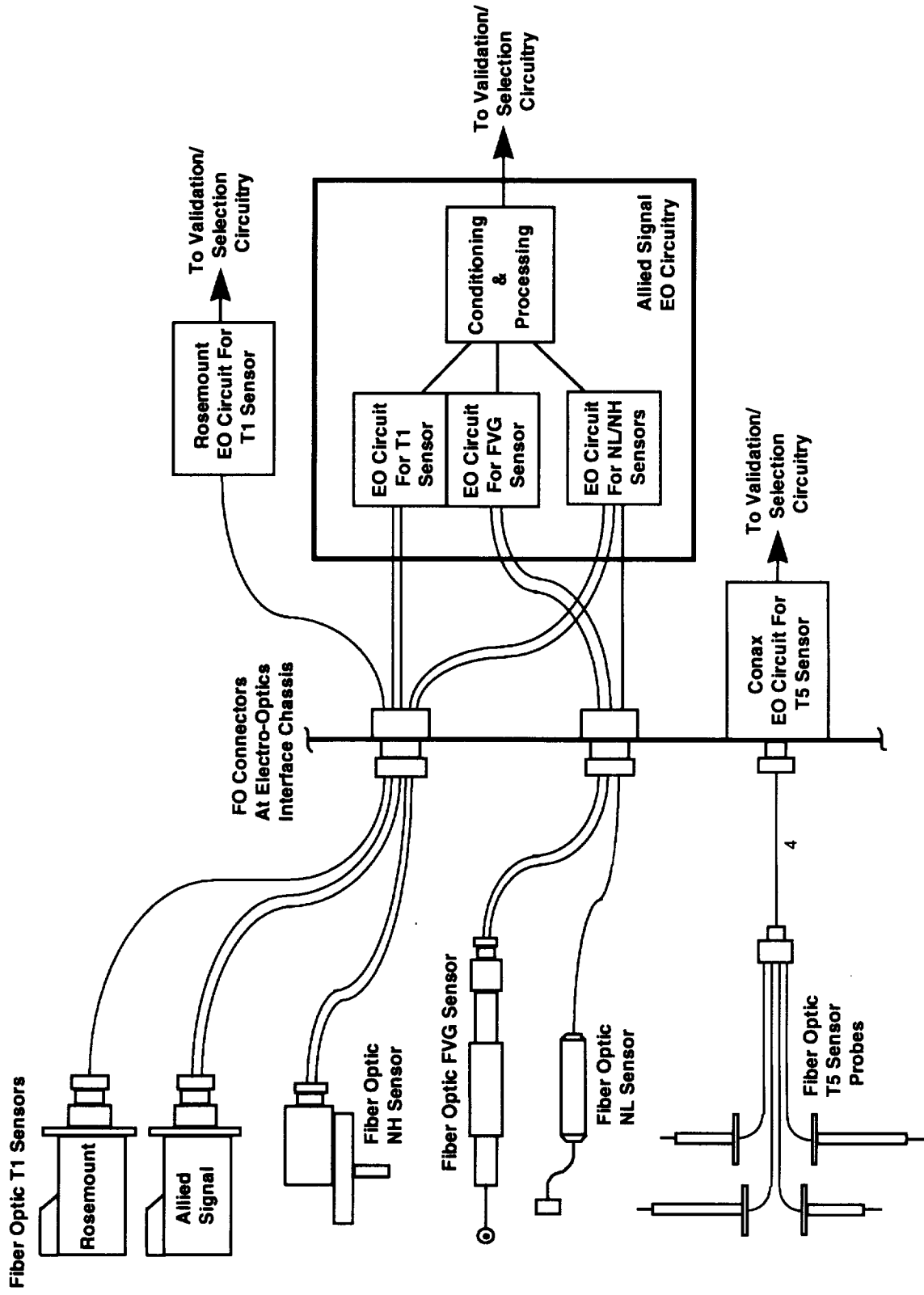


Figure 22 - Fiber Optic Interconnections

7.0 CONTROL SYSTEM DESCRIPTION

Two design reviews were conducted through the GE Aircraft Engines Chief Engineer's Office to examine the functionality of the EOI and its integration into the F404 control system. For each review, Lockheed Martin and Allied Signal were both present to review interface requirements.

7.1 CONTROL MODES

Two control system operating modes are defined as follows:

1. Normal/Reversionary Mode (fail-safe) - The engine control system is using all normal F404 sensor signals. The normal signals pass directly through the EOI relays to the ECU.
2. Optical Mode - The engine control system is using one or more validated fiber optic sensor measurement, converted to analog format compatible with the ECU, in place of its respective normal F404 signal counterpart.

7.2 FUNCTIONING OF THE OPTICAL SIGNALS IN THE F404 CONTROL SYSTEM

Following is an overview description of how the signals provided by the optical sensors function in the F404 control system. Figure 23 is a schematic description.

7.2.1 NL Speed Signal

At part power and lower operation, the level of NL floats, being aerodynamically tied to NH speed. It is corrected by T1 to schedule FVG angle. At IRP and above, it is compared with the NL schedule to compute a NL error. Fuel flow is adjusted to maintain the NL schedule and to activate NL over-speed logic. During a slow throttle advance, NL reaches its scheduled limit just prior to IRP.

7.2.2 FVG Position Signal

This signal is used to provide feedback for the closed-loop FVG position control. The FVG position feedback is compared to the FVG position schedule which is designed to optimize engine performance and operability. The ECU positions the FVG actuator to achieve zero error between the FVG position schedule and feedback measurement.

7.2.3 T5 Temperature Signal

This signal is used to provide HP and LP turbine protection against adverse temperature levels. It is compared to the maximum T5 limit schedule to compute a T5 limit error. The ECU modulated the exhaust nozzle area based upon the T5 limit error to maintain a T5 temperature below the T5 limit schedule. During a slow throttle advance to IRP, T5 reaches its limit just prior to IRP. Generally, this occurs at T5 temperatures above 1250°F where the Conax sensing system is accurate.

The signal is also used to detect main combustor and AB flameouts, and provides indication of hot starts and post shutdown fires. Although the Conax sensing system is limited in how low it can measure, Conax designed this program's system to provide engine start indication (not accurate) as low as 600°.

7.2.4 T1 Temperature Signal

This signal is used to generate a corrected NL calculation that is used in FVG position angle scheduling. It is also the primary independent variable in the T5 limit schedule and NL limit schedule and a component in the AB fuel scheduling.

7.2.5 NH Speed Signal

This signal indicates acceptable conditions for ignition (10% to 45%), when to de-energize the NL over-speed solenoid, and interlock of NL sensor failure logic. NH is aerodynamically limited by maximum T5, NL, and PS3.

7.3 VALIDATION OF OPTICAL SIGNALS

Validity of the optical signals is executed through the EOI software structure as discussed in paragraphs 8.6. Optical and F404 electrical signals (except T5) are tracked and compared. Validation of the optical sensors requires steady state and dynamic sensing system variations to be accommodated, including during rapid transients.

Instead of tracking and comparing T5 optical and electrical signals, the approach for T5 is to allow use of the optical measurement if the electrical T5 measurement does not exceed the T5 limit. The comparisons are made in EOI software. If the optical measurement sent to the ECU is erroneously high, the limit will not be reached and the

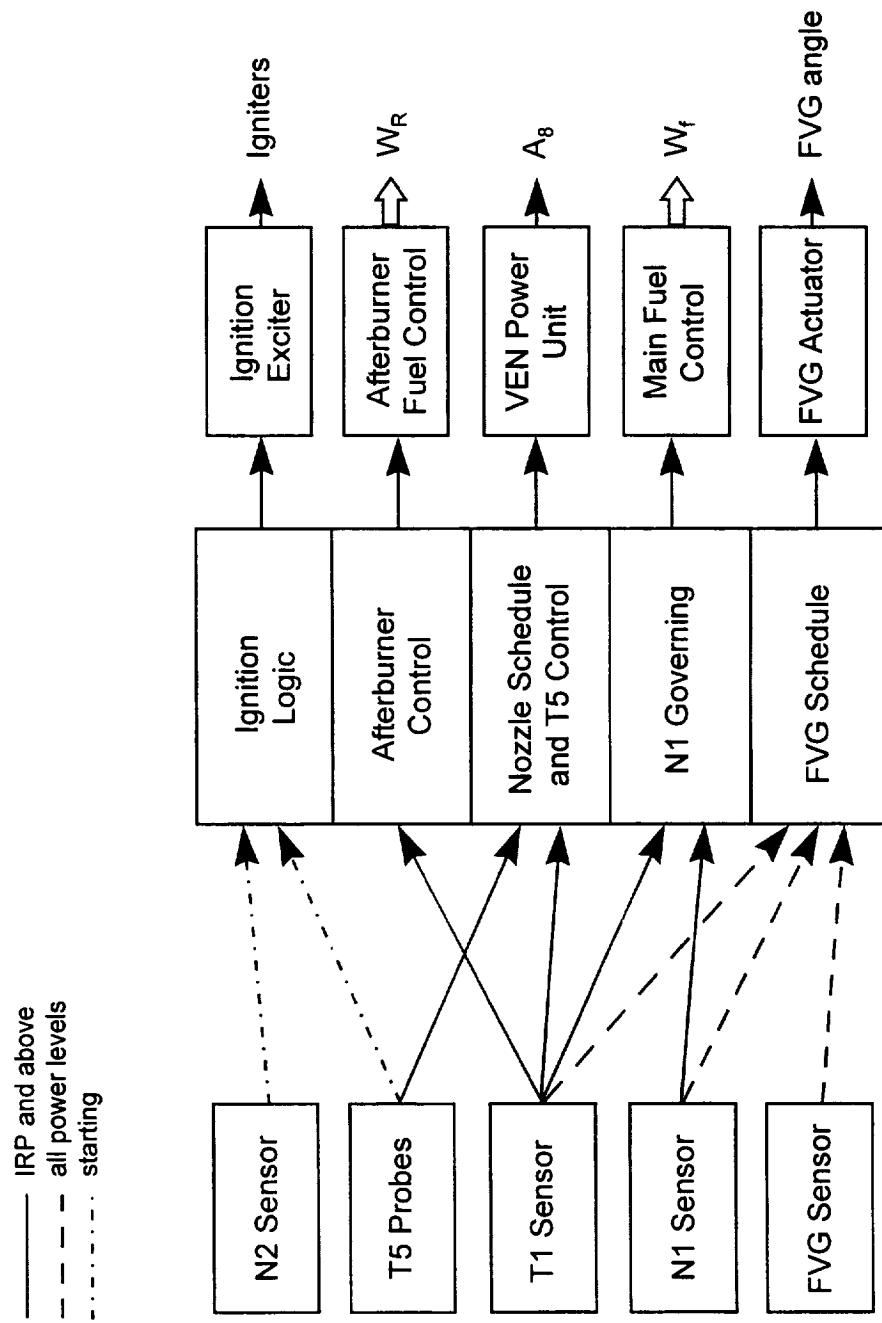


Figure 23 - Possible Functions of the Optical Sensor Signals In the F404 Engine Control System

engine will run cold, with some loss of power. If the optical measurement is erroneously low, the EOI will sense that the T5 limit is reached and revert to the normal mode, insuring safe operation.

7.4 OPTICAL SENSOR ACCURACY REQUIREMENTS

Assistance was received from GE Lynn F404 Systems Engineering to recommend acceptable operating tracking tolerances between the normal F404 and the optical sensor signals. This assumes that the control system limit schedules for T5 and NL are adjusted as described in paragraph 7.8.2 and that the recommendations are approved following a planned GE Readiness Review before the planned engine test takes place.

The suggested tolerances relate directly to the EOI software error limits used in validating the optical sensor signals (see paragraph 8.6). Bias and gain adjustments to the optical signals are available through the EOI software (see paragraph 8.4). It is planned that EOI bench and baseline engine testing will indicate any adjustments required for acceptable signal tracking.

The recommended tracking tolerances are:

- NL \pm 5% - A -5% tracking error will result in the fan maxing out at normal IRP levels. A +5% error is important in limiting FVG tracking error. The optical NL sensor should track well within this tolerance.
- FVG \pm 2 degrees - This translates to \pm 0.108 inches stroke. The optical FVG sensor is very accurate. Rigging to this accuracy should not be a problem. This error, along with T1 and NL errors, results in a total possible \pm 5% FVG error, which is safe to run based on previous testing.
- T5 \pm 20°F - A -20°F tracking error will result in T5 maxing out at normal IRP levels. A +20°F error is not important since AB operation is not planned. The optical T5 sensor should track within this, especially in the upper more accurate range.
- T1 \pm 5°F - This is acceptable during normal transient operation and for short duration steady-state operation. The optical T1 sensor should track well within this tolerance.

Note: To account for being outside the engine airflow path, the optical T1 sensor signal is

adjusted through the EOI software using an estimated recovery factor based on fan speed.

- NH + 5%, -10% - The optical HN sensor should track well within this tolerance.

7.5 CONTROL LOOP STABILITY

During the planned engine testing in the optical mode, the optical NL, FVG, T1, and T5 sensor signals will be inputs to the F404 engine control system. The optical sensors will contribute phase shift, more or less than the normal electrical sensors. In addition, the EO circuitry and the Lockheed Martin analog/digital circuitry will add phase shift.

System designed phase margin was provided by GE Lynn F404 Dynamics engineers. The transfer functions of the new/added components were determined and their effect on phase margin assessed. The EOI software includes adjustable signal compensation and filtering logic (see paragraph 8.4) in case it is needed to maintain sufficient phase margin and ensure stable engine operation.

The most important example of the importance of signal dynamic characteristics to engine stability is FVG position. The F404 FVG control loop requires response at frequencies much higher than the other three signals. The speed of processing the optical FVG position signal must be sufficient to provide proper response characteristics for normal engine system characteristics. The optical FVG subsystem (from actual position to software parameter) consists of the sensor, the Allied Signal EO circuitry, and the Lockheed Martin D/A conversion circuitry. The combined dynamic response characteristics must be compatible with testing planned in the F404 control system.

The Allied Signal EO circuitry provides a 5 millisecond FVG position data update rate. This transport lag corresponds to signal phase shifts as shown in Figure 24, for example, a 9 degree phase shift at 5 Hz. Analysis shows that the phase margin designed into the FVG control loop is sufficient such that the optical FVG subsystem is expected to be capable of use for closed-loop control without affecting control stability during normal engine operation.

7.6 SENSOR SYSTEM TIME RESPONSE REQUIREMENTS

Assistance was received from GE Lynn F404 Systems Engineering to determine engine operational effects of time response differences between the normal system and the fiber optic system, especially for FVG/T5/T1.

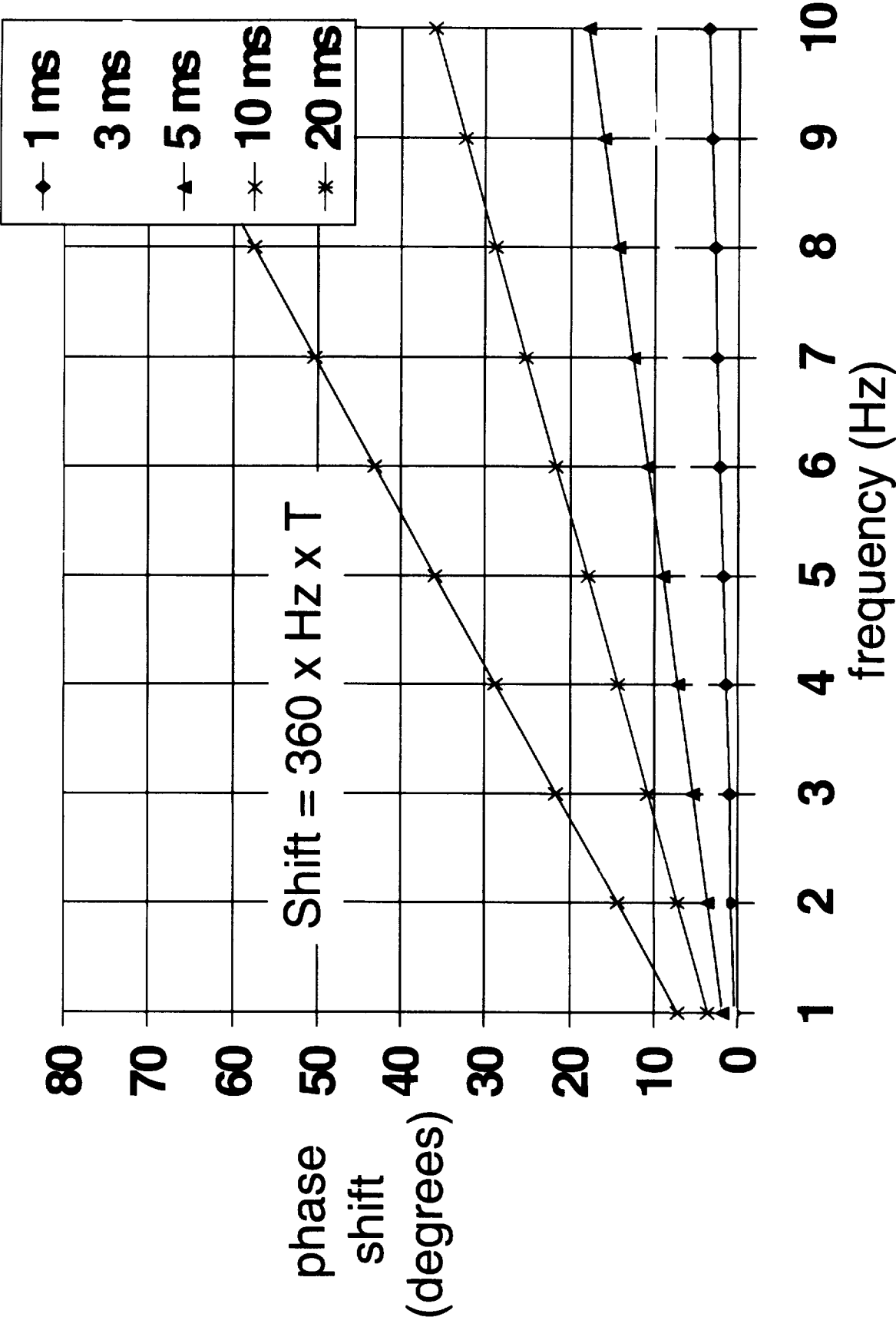


Figure 24 - Phase Shifts Resulting From A Pure Transport Lag T In Milliseconds

7.6.1 FVG Sensor

The maximum slew rate required of the F404 FVG actuator at sea level is about 80% of stroke per second or 2.16 inches/second. Successful signal processing at this velocity was demonstrated during the dynamic testing at CRL described in paragraph 3.5.5

7.6.2 T5 Sensor

T5 signal dynamics affect performance and stability of the engine. A component test was run to compare the time response of the T5 thermocouple probes with that of the T5 optical probes (see paragraph 3.2.6). The plan is to compare data after baseline engine testing (see paragraph 11.6.1) to determine if a software adjustment is needed to allow the optical probes to be used in F404 engine control system testing.

7.6.3 T1 Sensor

Differences between optical and normal F404 electrical T1 sensor dynamics for control system operation is not considered a concern for engine ground testing. During an engine ground test, the range of T1 measurements will be small and, excluding recovery, inlet temperatures are not expected to change rapidly.

7.7 MAINTAINING NORMAL ECU FUNCTIONALITY

Assistance is being received from Lockheed Martin, Ft. Wayne, IN, where the F404 ECU was designed and is tested/produced, to address issues associated with maintaining proper ECU function as integrated with the EOI for this program. These are planned to be included in a Hazard Analysis to be completed and reviewed before the planned engine ground test. Some of the issues are described below.

7.7.1 EOI Faults/Signal Glitches

The optical closed-loop control engine demonstration strategy depends upon the normal F404 signals passing straight through the EOI basically unmodified if, for example, there are faults in the optical system or if EOI power is shut off. An analysis is required to identify effects of internal EOI circuit failures as well as effects of normal to optical and optical to reversionary signal transition glitches.

7.7.2 EOI/ECU Power Sequencing

The effects of signal transmission from the EOI to the ECU when the ECU is unpowered is unknown and difficult to determine. Since switches between the ECU and sensors are just being opened and closed, a problem is not expected. However, a mechanism is in place to prevent such transmission as follows. Electrical excitation for the F404 T1 RTD is routed from the ECU through the EOI. All EOI signals outputs are prevented from transmission to the ECU unless this RTD excitation circuit is active, indicating a powered ECU.

7.7.3 The NL Signal Phase Shift

- **F404 System Requirements**

Due to the way the ECU simultaneously processes the two NL signals, there is a limit to the combination of how much phase shift between the two signals and waveshape \pm asymmetry can be tolerated before extra pulses are detected (an erroneously higher speed) and poor (but not unsafe) engine operation results. Phase shift is introduced mechanically (maximum of about $\pm 6^\circ$) by tolerances in the sensors' mounting locations, tolerances in fan blade spacing, and perturbations in fan blade position (vibration) during engine operation. If both signals have perfect 50% - 50% duty cycles (more so at higher speeds), the phase shift limit is up to 180° (minus the mechanical effects). If the signals have 20% - 80% duty cycles (never this bad and more so at lower speeds), the phase shift limit is $\pm 72^\circ$.

- **Effects of Adding the Optical Sensing System**

The optical NL modulator itself adds negligible ($< 1^\circ$) phase shift from the electrical excitation split off input from one of the F404 NL sensors to its optical output. The only precaution is to check for correct polarities.

The major contributor to additional phase shift in this program is the Allied Signal EO processing circuit. Filtering is used to block out possible low frequency engine vibration induced effects (max one per rev NL is about 220 Hz) and high frequency noise, and pass the speed signal range of from about 1860 Hz to 11,150 Hz. The chosen filter has a phase shift characteristic ranging from near zero degrees at 1500 Hz to just over 50° at 11 kHz which is compatible with the requirements described above.

7.8 ECU MODIFICATIONS

7.8.1 Analog NH Signal

The optical NH core speed measurement is planned to be validated in the EOI using an F404 electrical core speed signal obtained from within the ECU. This signal is to be broken out from its normal internal ECU path and wired to the ECU J61 test connector. The return NH signal from the EOI, whether the identical electrical signal that went out (EOI normal mode) or a signal generated from the optical speed measurement (EOI optical mode), is to return through the ECU J61 connector back to the breakout point. Lockheed Martin, Ft. Wayne, has defined the required ECU wiring modifications and is to perform the modifications prior to the EOI/ECU system test, the plan for which is described in Section 10.0

7.8.2 Adjustment Pots For NL/T5

In order to allow a greater tracking error between the

normal F404 and the optical sensor signals (see paragraph 7.2), GE Lynn F404 Systems Engineering recommended that the engine be operated 5% (664 rpm) below the NL limit schedule and 20 degrees below the T5 limit schedule. This is not thought to affect the realization of this program's planned demonstrational engine testing goals. These recommendations are planned to be reviewed at a GE Readiness Review before the planned engine test takes place.

Implementation of the above described limit changes requires the adjustment of pots in the F404 ECU. After receiving approval, it is planned that the adjustments be accomplished and confirmed as part of the EOI/ECU system test at Lockheed Martin, Ft. Wayne, IN, as described in Section 10.0.

8.0 EOI SOFTWARE

8.1 DEVELOPMENT PROCESS

Generation of the EOI software by Lockheed Martin, Johnson City, NY, from the GE EOI Software Definition Document (ref. 1) required a process including:

- Generating a Terminal Interface Program (TIP) to enable communication with the processor.
- Creating build tools, a process for compiling and linking the many assembly modules and files.
- Memory organization.
- Operating system and application software module coding, review, informal testing, and debugging.
- Coding and testing the MIL-STD-1553B transmit and receive bus handler.
- Built-In-Test processing procedures.
- Software integration with the digital module hardware.

The paragraphs below provide highlights from the GE EOI Software Definition Document, a comprehensive definition of the EOI software content and its operation for the F404 optical closed-loop propulsion control demonstration system.

8.2 SYSTEM CHARACTERISTICS

The programming language utilized is 68020 Assembly Language. The minor frame size available to execute the signal processing instructions is nominally 5 milliseconds. Each sensor data processing cycle (major frame) consists of three minor frames. Each minor frame includes T5 analog/optical and FVG analog/optical processing, while NL analog/optical, NH analog/optical, and T1 analog/optical are processed in each minor frame respectively, once each cycle of 15 milliseconds, as follows:

	T5	FVG	NL	NH	T1
minor frame #1	x	x	x		
minor frame #2	x	x		x	
minor frame #3	x	x			x

8.3 INPUT SIGNAL CONVERSIONS

Analog sensor input signals are received from the normal F404 engine sensors, processed, and converted to digital signals. Digital signals representing the optical sensors measurements are received from the EO circuitry. These digital signals are converted to compatible temperature, position, or speed units. Each signal is then potentially biased by a separate NVM calibration

adjustment. Provisions are made to switch to MIL-STD-1553B data bus provided signals to test EOI system functionality.

8.4 SIGNAL COMPENSATION/BIAS

The purpose of this process is to improve the quality of the sensor signals. An NVM adjustable filter and lead compensation function (independent for each signal) is used to reduce the input signals' noise level and reduce their phase shift due to introduction of the EOI into the F404 ECU sensor path. A signal bias function is also employed to provide the capability for fine tuning the signals to eliminate expected and unexpected signal errors through the EOI.

8.5 SIGNAL RANGE CHECK

The purpose of this process is to aid in the determination of sensor signal validity by comparing to NVM adjustable high and low range limits. If a signal sustains an out-of-limits condition for the NVM adjustable persistence period then the signal's range fault flag is set.

8.6 SIGNAL VALIDATION

This process determines the operational status of each of the optical signals. The status is based upon the results of:

- (1) parameter range tests,
- (2) optical sensor built-in-tests, and
- (3) optical versus analog sensor comparison tests

The validity of the optical sensor signal is then used in the signal selection process to determine the EOI output source for each of the five sensed parameters.

Comparisons between the normal F404 sensor measurements and the optical sensor measurements are direct in all cases except T5. If the error between the signals does not fall within an adjustable upper and lower limit, then the optical signal is determined to be invalid. In the case of T5, the comparison is made between the normal F404 signal and the ECU's T5 limit schedule.

8.7 SIGNAL SELECTION

This process generates the signal relay and switch

position commands for the EOI output signal source selection between the normal F404 sensors and the optical sensors. Source selection is based upon the determined validity of the optical sensor signal as well as the receipt of optical sensor permission signals from a remote MIL-STD-1553B data bus terminal input. Selection of the optical sensor signals is based upon:

- (1) the signal validity state set in the validation process described in paragraph 8.6,
- (2) the sensor EO module built-in-test status, and
- (3) the EOI built-in-test status

The optical sensor permission signal is structured such that each sensor signal can be permitted independently or simultaneously. The default selection for all of the signals is the normal F404 sensor.

8.8 OPTICAL SIGNAL OUTPUT CONVERSION

This process prepares the conditioned fiber optic T5, T1, and FVG signals for conversion from a digital format to an analog output, compatible with subsequent D to A conversion. The optical T5 signal is converted from °R to millivolts and then biased by the EOI T5 cold junction temperature. The optical T1 signal output is selected between the Allied and the Rosemount sensor inputs. The optical FVG signal output is converted from degrees of rotation to a LVDT signal rms voltage.

8.9 SIGNAL SWITCHING

For the T1 and FVG signals, sensor output selection is controlled by an analog relay that switches between the normal F404 sensor signal and the optical sensor signal. Progression between the two signals is controlled such that

the output signal transitions from the normal F404 signal to an average of the normal and the optical measurement to solely the optical signal measurement. This reduces the size of discontinuities. A reverse of this transition occurs when switching back to the normal sensor. If the selected optical measurement is determined to be invalid or if the EOI BIT status is faulted while the optical signal is selected, then the EOI output automatically reverts to the normal F404 sensor.

For the T5 signal, sensor output selection is controlled by four analog relays that switch between the normal F404 sensor measurement and the optical sensor measurement. Because of the nature of thermocouple signals, a transition from normal to average to optical is not possible.

The switching process for the NL and NH signals is similar to that for FVG and T1 except that the relay switching process transitions from the normal F404 oscillating signal to a $\pm 5V$ version of the normal F404 oscillating signal to a $\pm 5V$ oscillating signal derived from the TTL signal resulting from detection of the optical signal on the Allied Signal EO module (see paragraph 4.1.2).

8.10 ADJUSTMENT PARAMETERS

The EOI provides the capability to modify the contents of both operating RAM and many permanent NVM locations via a remote MIL-STD-1553B terminal in order to provide the flexibility of modifying the signal process logic without disrupting the software architecture. RAM adjustable parameters are set to nominal values during the initialization sequence. Subsequent changes are retained until an EOI power-down cycle. The modified values of NVM adjustable parameters are retained following a power-down.

9.0 EOI ACCEPTANCE TEST PLAN

9.1 PURPOSE

The purpose of the EOI acceptance test is to demonstrate acceptable functionality with respect to accuracy, dynamic response, adjustments, and logic functions. The paragraphs below provide an overview of the detailed plan for this testing intended to be performed following EOI assembly and successful hardware/software integration.

9.2 CONTINUITY

Because of the engine cabling configuration, three particular signals (FVG servo valve torque motor current, FVG LVDT excitation, and T1 sensor excitation) not involved in the sensor measurements will always pass directly through the EOI. Proper continuity resistance is to be checked across the appropriate 10 pin pairs.

To insure that the conductors of the above three signals are properly insulated, a measurement will be made to demonstrate sufficient resistance between the conductors and the EOI chassis.

9.3 ELECTRICAL SENSOR SIGNAL THROUGH-PUT WITH EOI UNPOWERED/POWERED

In the normal/reversionary (fail-safe) mode, the five normal F404 sensor signals are to pass directly through the EOI relays to the ECU, with the EOI either powered or unpowered (28 VDC). This test will simulate each electrical sensor input and confirm accurate, over-range, throughput, both individually and as a group of five. In addition, accurate transmission of MIL-STD-1553B data representing the monitoring of each electrical signal will be verified.

9.4 OPTICAL SENSOR INPUT

These tests are to confirm accurate, over-range, processing of each optical sensor signal into digital format through transmission of MIL-STD-1553B data representing each optical sensor parameter. The optical NH and T5 sensor inputs will be optically simulated using devices supplied by Allied Signal and Conax; actual signals require implementation on the engine. The optical NL, T1, and FVG sensor inputs will use the actual sensors.

9.5 OPTICAL SENSOR SIGNAL VALIDATION & RELAY ACTIVATION

In this test, all five electrical and optical sensor inputs are to be reset, and confirmed through representative MIL-STD-1553B transmitted data, to respective values slightly different but within the optical sensors' validatable tolerances. The EOI analog output signals are to be confirmed to be the electrical sensor values. Following appropriate software reset, each optical signal should indicate a status of valid.

The above action will enable the position of each output relay to be moved from electrical to optical, after an appropriate time delay. Each EOI output signal will first become a conditioned version of its respective F404 electrical signal. This preliminary step is done so that subsequent switching from electrical to optical is smoother and less likely to affect ECU functionality. During each relay or switch transition, the EOI analog outputs are transiently monitored to observe the nature of any discontinuities.

9.6 SWITCHING FROM ELECTRICAL TO OPTICAL

Using appropriate MIL-STD-1553B EOI receive permission steps, each optical switch will be closed and each electrical switch opened, permitting the EOI analog representation of each optical signal to become the EOI output. A shift in each output value will be observed, since the electrical and optical signal inputs were intentionally offset. The EOI digital (MIL-STD-1553B) and analog outputs will then be compared over a range of optical sensor inputs by overriding the validation requirements.

Finally, with validation overrides removed, each optical signal will be increased until relay/switch reversion to the electrical signal occurs. Error limits will be confirmed in both increasing and decreasing directions.

Successful switching will be confirmed on an individual electrical/optical signal basis and using all electrical/optical signals at once.

9.7 OTHER LOGIC VERIFICATIONS

This will include setting and confirming functionality of typical signal filtering and lead compensation, signal biases, and signal range checks.

10.0 EOI/ECU SYSTEM TEST PLAN

10.1 PURPOSE

The purpose of the EOI/ECU system test is to significantly reduce risk at the engine test by measuring the following effects of having the EOI interfaced with the ECU and determining the acceptability of those effects on ECU functionality. The testing requires the use of a F404 ECU test stand, located at Lockheed Martin, Ft. Wayne, IN.

1. Electrical loading effects with the EOI both powered and unpowered.
2. Accuracy of the EOI output signals using the normal F404 electrical sensor inputs.
3. Accuracy of the EOI output signals using the optical sensor inputs.
4. Signal glitches during switching between use of electrical and optical sensor inputs.

The paragraphs below provide an overview of the detailed plan for this testing intended to be performed following EOI acceptance testing.

10.2 ECU BASELINE TESTS

First, without any interconnection with the EOI, and before modification, a routine ECU functional test at room temperature is planned to be performed to establish the ECU's characteristics as received from NASA Dryden. After the modifications as described in paragraph 7.8, the functional test will be repeated to confirm the modifications.

10.3 ELECTRICAL SENSOR SIGNAL THROUGH-PUT WITH EOI UNPOWERED/POWERED

In the normal/reversionary (fail-safe) mode, five normal F404 sensor signals will be input to the EOI, pass directly through the EOI relays, and be output to the ECU, with the EOI both powered or unpowered (28 VDC). This test is intended to confirm that this will happen with negligible effect on ECU functionality. The test consists of repeating the routine room temperature ECU functional test with the EOI interconnected with the ECU as it is planned to be during the engine test, with the EOI both unpowered and powered. The results are to be compared with the results from paragraph 10.2, specifically noting any changes in those test sections related to the five subject input sensor

signals.

10.4 EFFECTS ON ECU SIGNAL READOUTS DURING SWITCHING TO USE OF OPTICAL T1, T5, AND NL SIGNALS

The F404 ECU transmits several analog signals to the test cell (aircraft cockpit) associated with engine condition monitoring. Among them are three of the sensor measurements used in this program, T1, T5, and NL. The routine ECU functional test includes paragraphs confirming the accuracy of these readouts.

For each of the three readout test paragraphs, while the ECU functional test is set up, an EOI input test parameter representing the corresponding optical signal, is set, validated, and switched through. During the switching action, the ECU readout signal is to be transiently monitored and recorded, with interest in the size of the discontinuity. While switched in, the optical test parameter is to be varied over range to confirm throughput accuracy. The ECU readout is to be transiently monitored again during reversion from the optical signal back to the normal signal.

10.5 CONFIRMATION OF ECU IGNITION LOGIC DURING USE OF THE OPTICAL NH SIGNAL

This test helps to confirm that the ECU is accurately receiving the optical NH signal. While running the routine ECU functional test associated with measuring the ignition logic trip point speed, an EOI input test parameter representing the optical NH signal, is set, validated, and switched through. The trip point is measured using the converted optical signal and compared with the trip point measured in the baseline tests.

10.6 ACCURACY OF ECU CONTROL SCHEDULE SETTINGS DURING USE OF OPTICAL SIGNALS

The routine F404 ECU functional test contains subtest paragraphs to confirm the accuracy of scheduling its control system parameters. Five such schedule tests involve one or more of the optical signals:

FVG Schedule
XNL - T1 Schedule
A8 - T1 Schedule
WFR Schedule
T1 - T5 Schedule

By slightly altering the routine test procedure, selected test points are planned to be repeated. For example, with the optical T1, NL, and FVG signals set at nominal values, and validated and switched through the EOI and into the ECU,

the resulting ECU open loop FVG schedule error will be a good measure of how well the optical signals are processed through the system.

11.0 ENGINE TEST PLAN

The paragraphs below provide highlights of the detailed engine test plan, which is planned to be reviewed at a GE Readiness Review before the planned engine test takes place.

11.1 TEST OVERVIEW

The objective of the test is to demonstrate the capability of a system of optical sensors, electro-optic circuitry, and fiber optic cables to functionally perform in control system operation during a F404 engine ground test.

The test is planned to be coordinated by GE Aircraft Engines, Cincinnati, Ohio, under a GE/NASA Space Act Agreement. Optical control system hardware, designed for use on a F404 engine and interface with its engine control unit (ECU), is to be supplied by NASA Lewis as deliverables under this program, contract NAS3-26617, Task Order 34. The engine is to be supplied by NASA Dryden. The test is planned to be performed at the GE operated Main Base Test Cell #2, Edwards AFB, by GE Flight Test Operation (FTO), personnel.

11.2 PARTS TO BE TESTED

Major components to be tested, as shown in Figure 25, are the following:

- | | |
|---|----------------|
| 1. Electro-Optic Interface, | 4013419-130G01 |
| 2. Optical NH Speed Sensor, | FXC-311079 |
| 3. Optical NL Speed Modulator, | 25000 |
| 4. Optical T5 Probe Harness Assembly, | 2SK-5660 |
| 5. Optical FVG Position Sensor, | FO3575-1 |
| 6. Optical T1 Temperature Sensor (Allied), | 1502699 |
| 7. Optical T1 Temperature Sensor (Rosemount), | 701J1 |

11.3 HARDWARE INSTALLATION

Description of the installations of the optical sensors is included in paragraphs 3.1.1 (T1), 3.2.4 (T5), 3.3.5 (NL), 3.4.4 (NH), and 3.5.3 (FVG) of this report. In addition, the optical NL modulator, being integral with a cable, is to be isolated from engine vibration because of its vibration sensitivity. The EOI is to be strapped to a platform under the engine.

11.4 OPTICAL SIGNAL CALIBRATIONS

With the EOI powered up and MIL-STD-1553B transmission, measurements from the optical FVG, T1, and NL sensors can be checked out. The optical T5 and NH sensors do not provide signals until the engine is running.

The optical FVG position sensor is to be rigged so that its active stroke coincides with the F404 FVG actuator, and adjusted to output a zero signal at the fully retracted, maximum open area, high speed, condition. The optical T1 sensor measurement is to be compared with ambient temperature. The optical NL modulator does not receive excitation until the engine is running, but its functionality can be checked using an oscillator.

11.5 DATA SYSTEM COORDINATION

Data to be available for display monitoring and printout during the test includes the full set of parameters from the EOI MIL-STD-1553B transmit subaddresses plus selections from the normal ECU/engine control room signals for comparison. A subset of the above is to be configured for transient recording on strip charts and for recording on tape for subsequent plotting and analysis.

11.6 TEST PROCEDURES

These procedures are designed to establish increasing confidence in the optical sensor measurements until all are permitted for use in the control system.

11.6.1 Baseline Tests

These tests are to occur after the normal functional checkout performed by GE FTO. The tests are to obtain an initial reference set of steady-state measurements of a selected set of the normal ECU/engine control room signals at particular engine settings as compared with measurements by the optical sensors as processed by the EOI, without ECU/EOI interconnection. Figure 26 shows the relevant F404 hardware and contract hardware installed for this testing.

The steady-state schedule is to consist of printing and recording the comparative data at five throttle settings from ground idle to intermediate (max dry operation) after a 15 second settling time. GE Engineering is to compare the data and make any bias/gain adjustments to enable subsequent optical sensor validations.

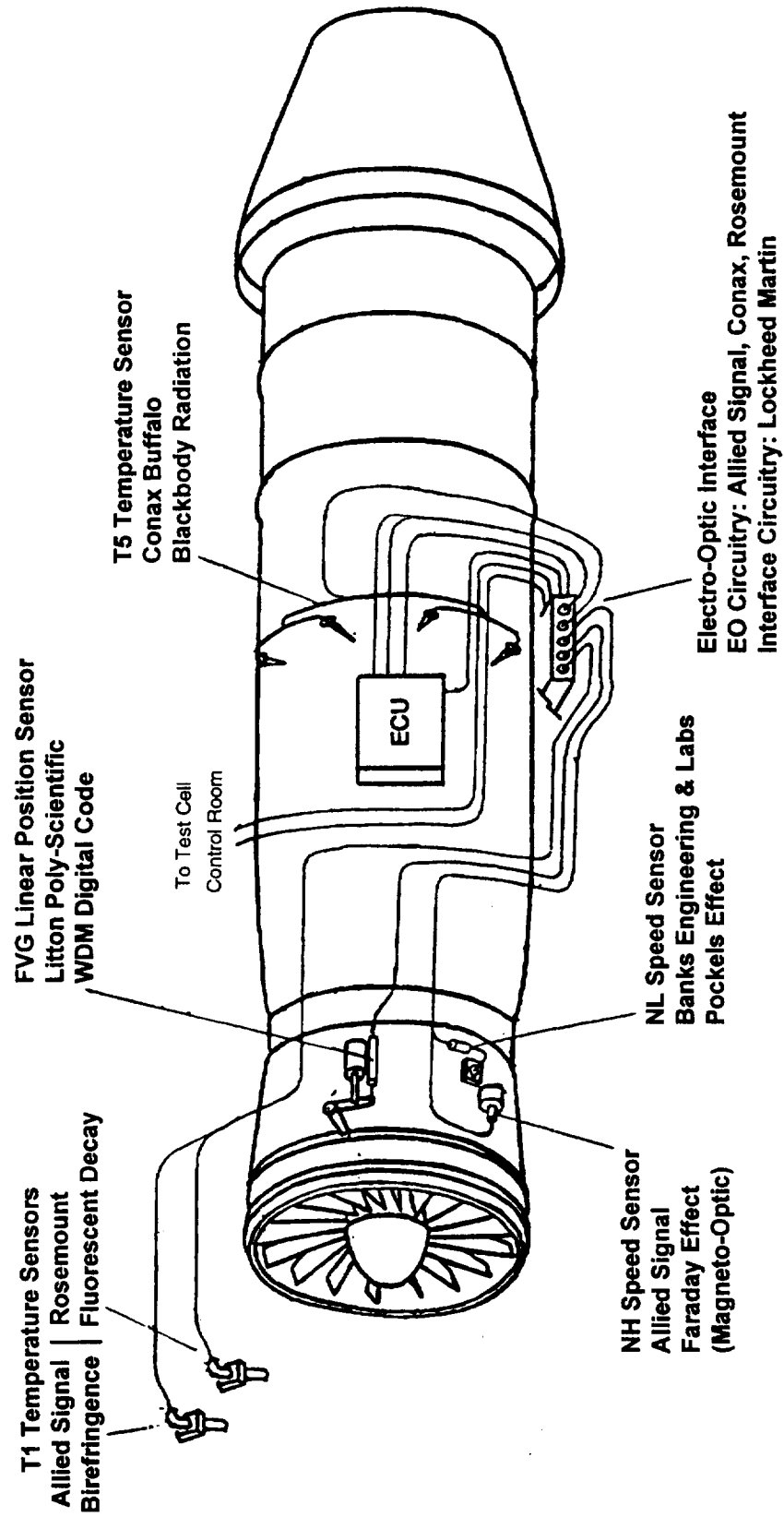


Figure 25 - Fiber Optic Sensors Planned For Testing On the F404-400 Engine

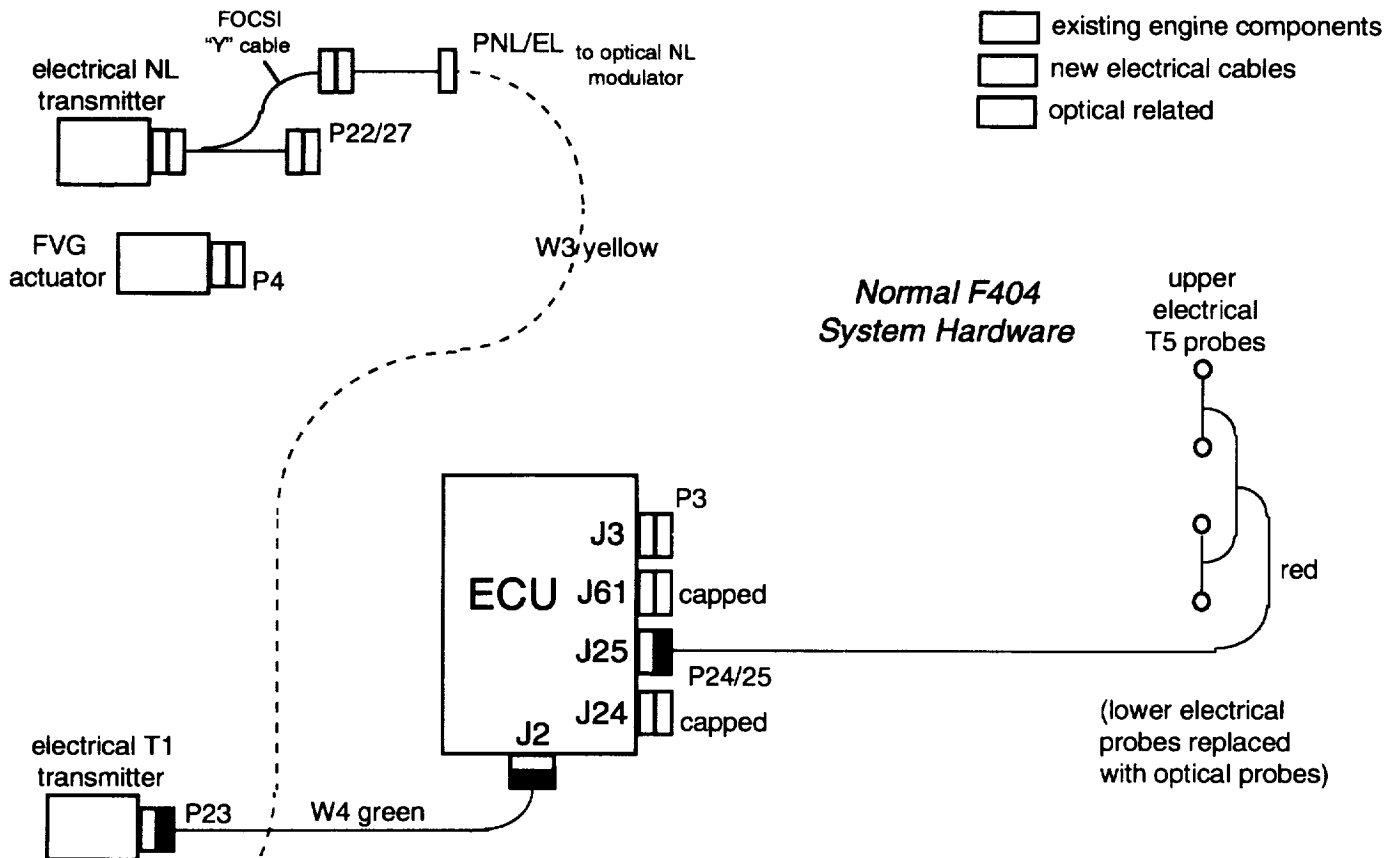
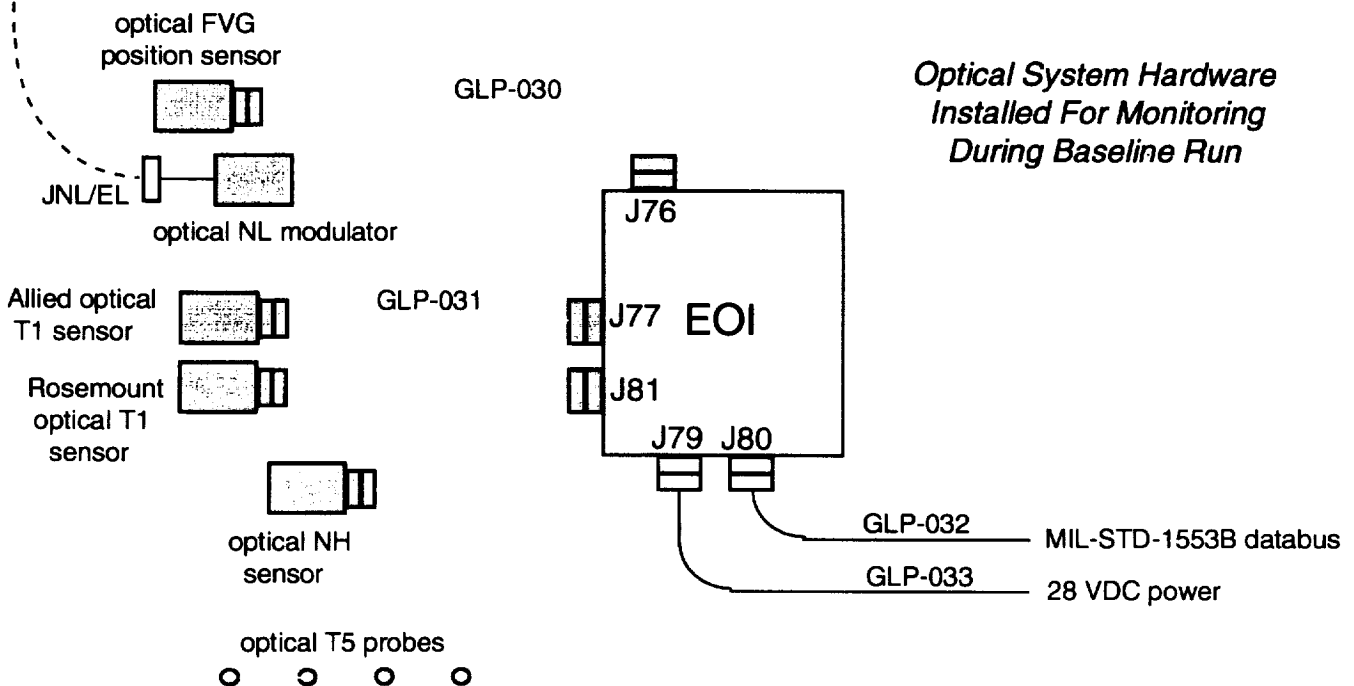


Figure 26 - Hardware Installed For Baseline Engine Runs



11.6.2 Transition To Having the EOI/ECU Interconnected & Powered

These tests are to determine any loading effects associated with the EOI/ECU interconnections that may prevent normal operation in the fail-safe reversionary EOI mode. For this, the five normal F404 signals are passing directly through the EOI relays. First, the steady-state schedule is to be repeated with the EOI fully interconnected to the ECU but without power. Secondly, the steady-state schedule is to be repeated again and the selected set of normal ECU/engine control room signals are monitored before, during, and after the EOI is switched "on" then "off". Figure 27 shows the relevant F404 hardware and additional contract hardware installed for this and all subsequent testing. GE Engineering is to make any adjustments to provide acceptable engine operation with the EOI powered on and repeat the above steps if necessary.

11.6.3 Optical Signal Validation

This test is to gain confidence in the optical signal measurements while operating in the normal mode, and to demonstrate that the optical signals remain validated (unfaulted) over the engine test range. With all optical signals validated, a selected set of the normal ECU/engine control room signals is to be compared with measurements

by the optical sensors while performing a steady-state schedule consisting of throttle settings from ground idle to intermediate.

GE Engineering is to note any conditions where the optical signals become invalidated, make any adjustments to prevent subsequent invalidations, and repeat the above steps if necessary. Using the recorded digital data, corresponding ECU/engine control room signals versus EOI (optical and electrical sensor signals) data pairs are to be compared.

11.6.4 Selection of Optical Signals

This test is to additively select and exercise each optical sensor in control system operation until all optical sensors are selected and exercised together. The order of selection is to proceed as follows: NH, T1, T5, FVG, NL.

Each selection process begins at ground idle. After confirming that the optical measurement is within validation limits, the electrical representation of the optical signal to be output from the EOI to the ECU is to be validated and permitted. During each action the normal ECU/control room signals are to be recorded on strip charts. With all optical sensors input to control system operation, the steady-state throttle step schedule is to be repeated.

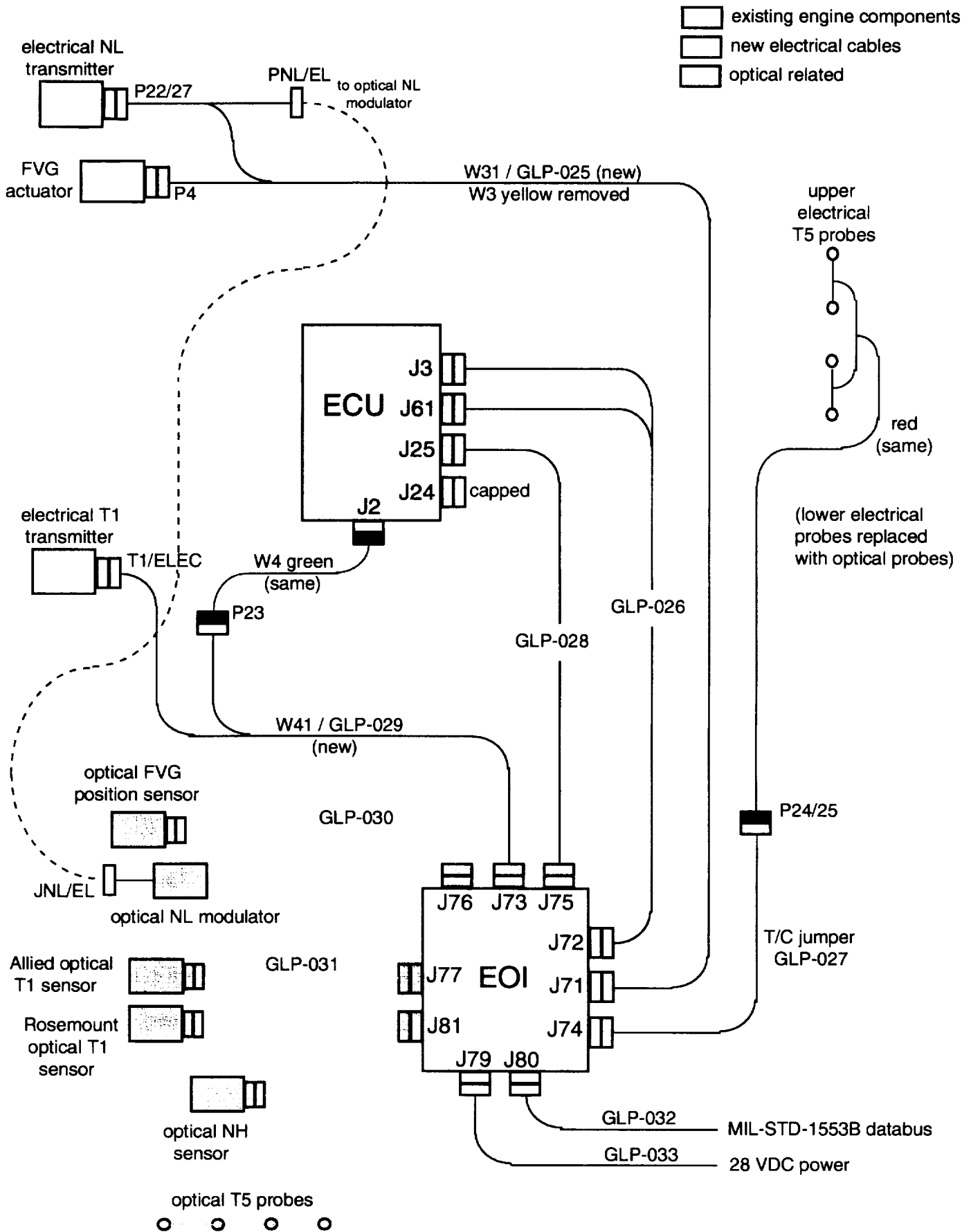


Figure 27 - All Hardware Installed

12.0 CONCLUSIONS

The subject of this report is to describe the work done under NASA Contract NAS3-26617, Task Order 34, that is, the design, fabrication, and testing of the optical and related hardware components and software required to demonstrate optical closed-loop control of a F404-400 turbofan engine during ground testing, by building on the experience of the NASA FOCSI program. The results provide a significant step in moving through the stages of optical technology development.

For this program, **optical component design improvements** provide confidence in improved sensor signals and measurements over those used for the FOCSI program.

1. The Conax Buffalo electro-optic (EO) circuitry for processing the T5 temperature blackbody radiation probe signals was redesigned to improve probe/circuit interchangeability, eliminate the need for a thermo-electric cooler, and extend the lower end of the measurement range to provide measurement of temperatures at engine idle.

2. The Banks Engineering optical fan speed modulator was redesigned to achieve a smaller insertion loss and a larger output signal ratio of modulation depth to optical DC noise, without the need for an integral electric transformer. These improvements were coupled with extensive bench testing with the Allied Signal EO circuitry during its development.

3. To improve confidence in obtaining a better quality optical T1 temperature signal, two techniques are being used: the Allied Signal birefringence and the Rosemount time-rate-of-decay (used on the FOCSI program). In addition, in both cases, the EO circuitry is supplied by the respective probe supplier.

For this program, a **control system strategy** was developed and implemented through software to provide validation of the optical signals and reversion to the normal engine sensors should faults in the optical signals or their processing occur. Optical signal validation is based on signal range tests, EO circuitry built-in-tests, and optical

versus normal sensor comparison tests. Tracking tolerance levels are planned to lessen validation restraints, yet insure normal engine operation. Bias and gain adjustments to the optical signals are available. Transients produced during switching between use of normal and optical signals are smoothed. Detected errors, faults, and invalidations result in immediate reversion to the unmodified straight-through normal F404 sensor signals.

For this program, confidence in **maintaining control stability during optical mode engine operation** is provided through analysis of the optical sensor signals and application of required compensation. The F404 control system control loops are designed to maintain sufficient phase margin. The design is modified by addition of the optical sensors and their processing circuitry. Wind tunnel testing was performed to compare the time response of the optical T5 subsystem with that of the normal thermocouple. Optical FVG sensor slew rate and sinusoidal response testing were performed. These testing results plus other analyses and computer simulations indicate no stability issues, although software compensation is available if future testing indicates otherwise.

For this program, **conversion of the optical signals into analog formats** compatible with the normal engine control interfaces was required. For validation, each optical signal is converted to digital format. In the optical mode, respective inputs to the engine control consist of the optical signals that have been converted to represent a thermocouple signals (T5), a resistive thermal device (T1), a linear variable differential transformer (FVG), or an oscillating frequency signal (NL/NH) of a compatible \pm voltage.

Detailed test plans are in place to demonstrate acceptable functionality of the optical and new electrical hardware components and software during bench testing, to confirm acceptable interfacing with an engine control during system testing, and to perform in closed-loop control system operation during a F404 engine ground test. There are no known technical barriers to realizing the planned demonstrational objectives.



APPENDIX -A

HARDWARE PHOTOGRAPHS

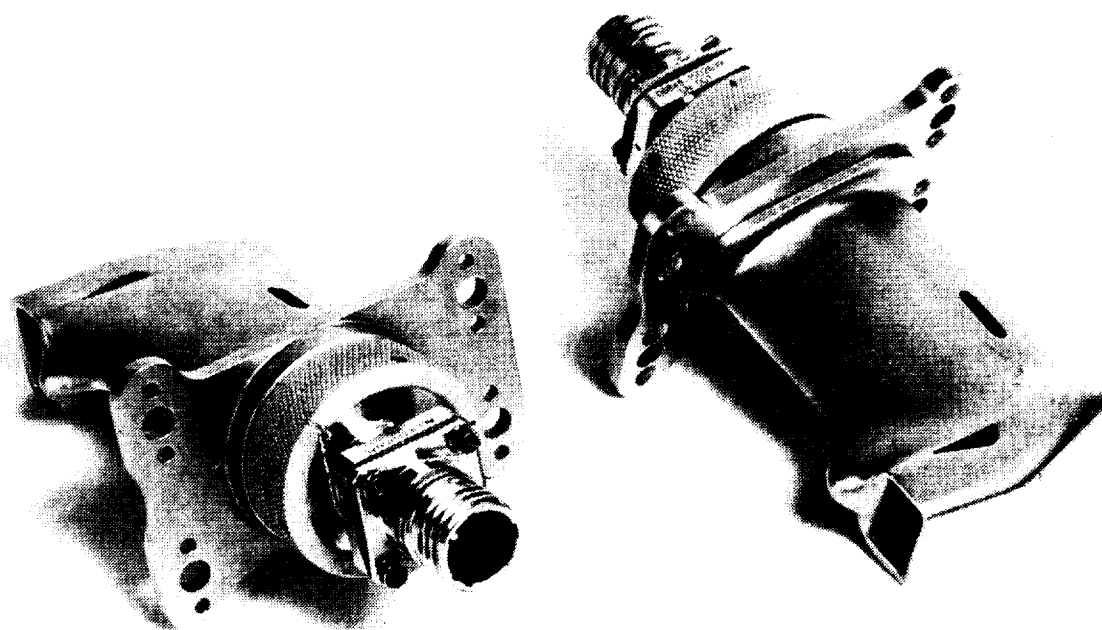


Figure 28 - Allied Signal's Optical T1 Temperature Sensor

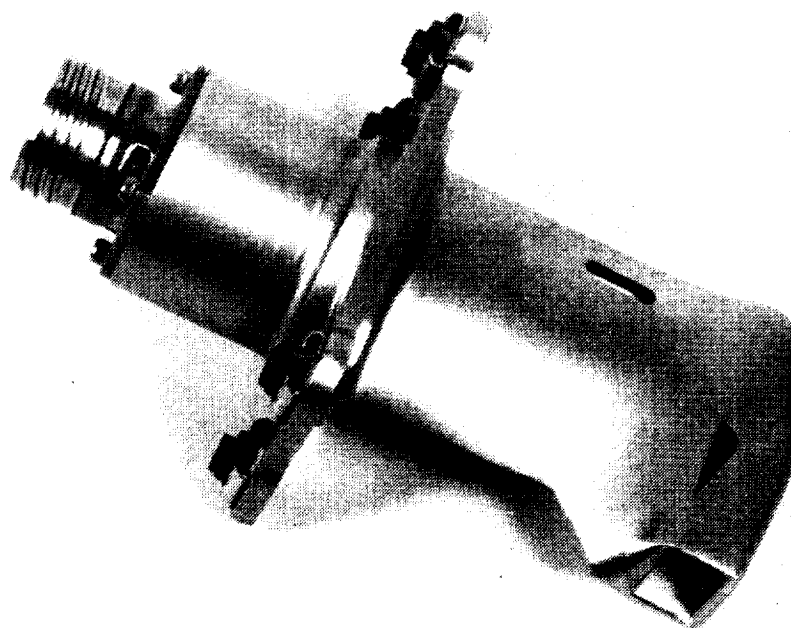


Figure 29 - Rosemount's Optical T1 Temperature Sensor

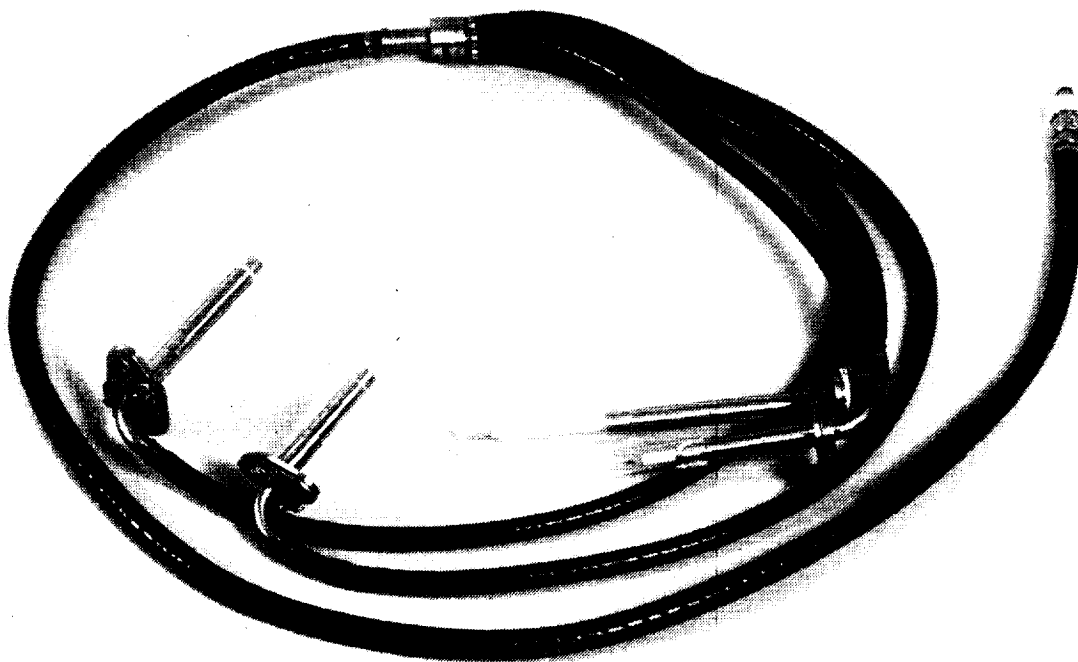


Figure 30 - Conax Optical T5 Temperature Probe/Harness Assembly

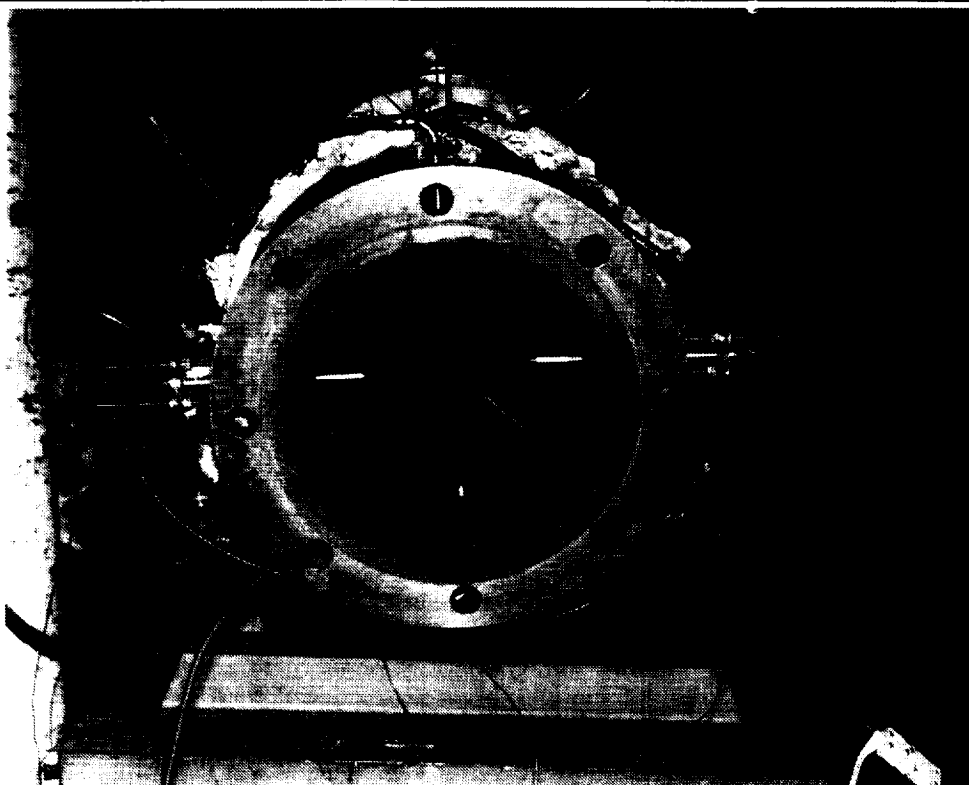


Figure 31 - Setup For Optical T5 Probe Time Response Test

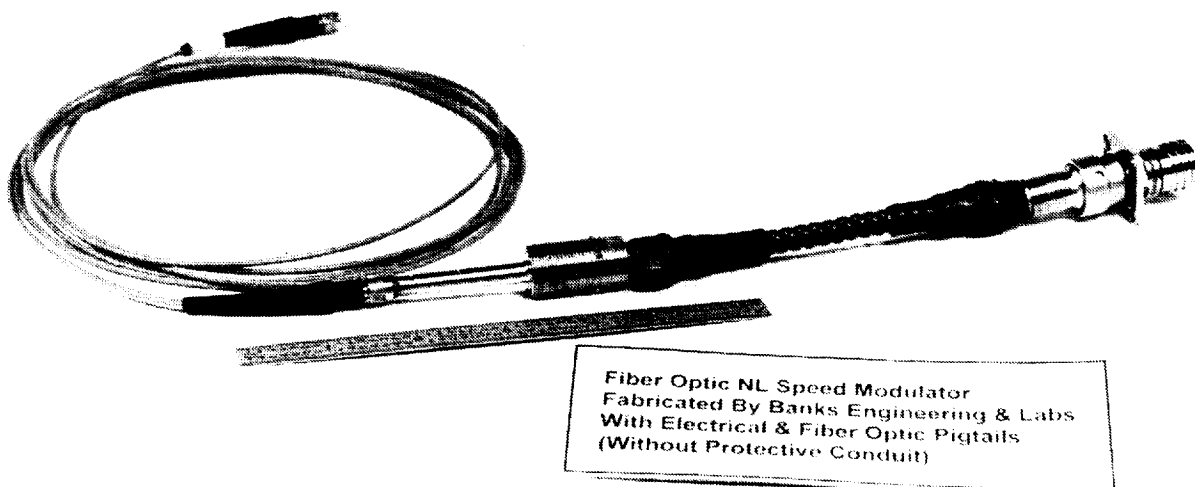


Figure 32 - Banks Engineering's Optical NL Modulator Assembly

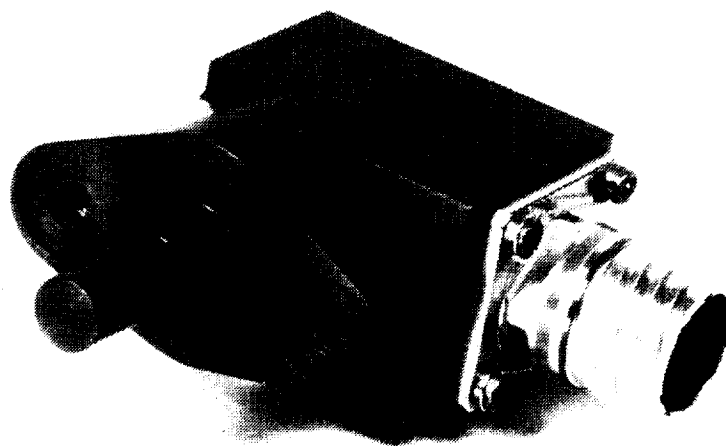


Figure 33 - Allied Signal's Optical NH Speed Sensor

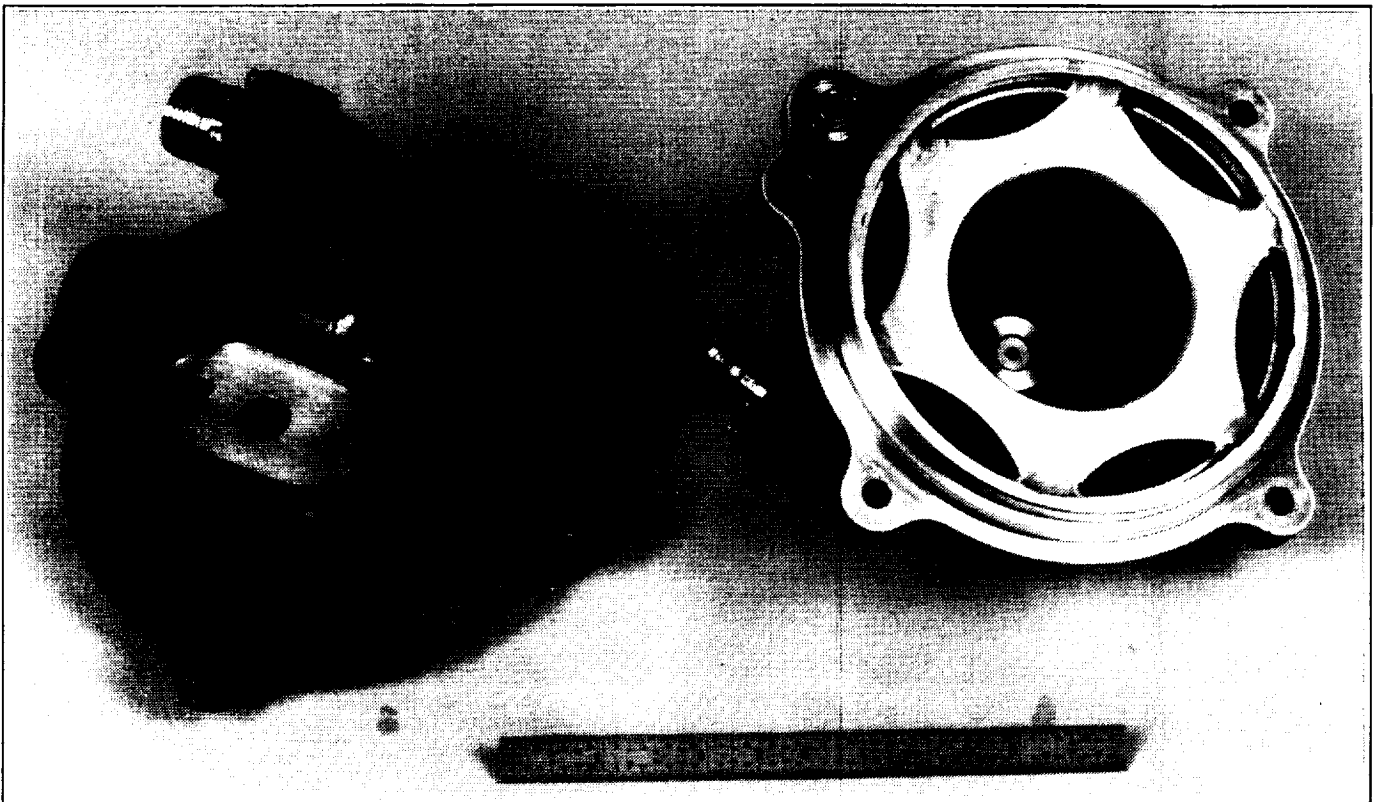


Figure 34 - Modified F404 Alternator Stator For Installation of Optical NH Speed Sensor

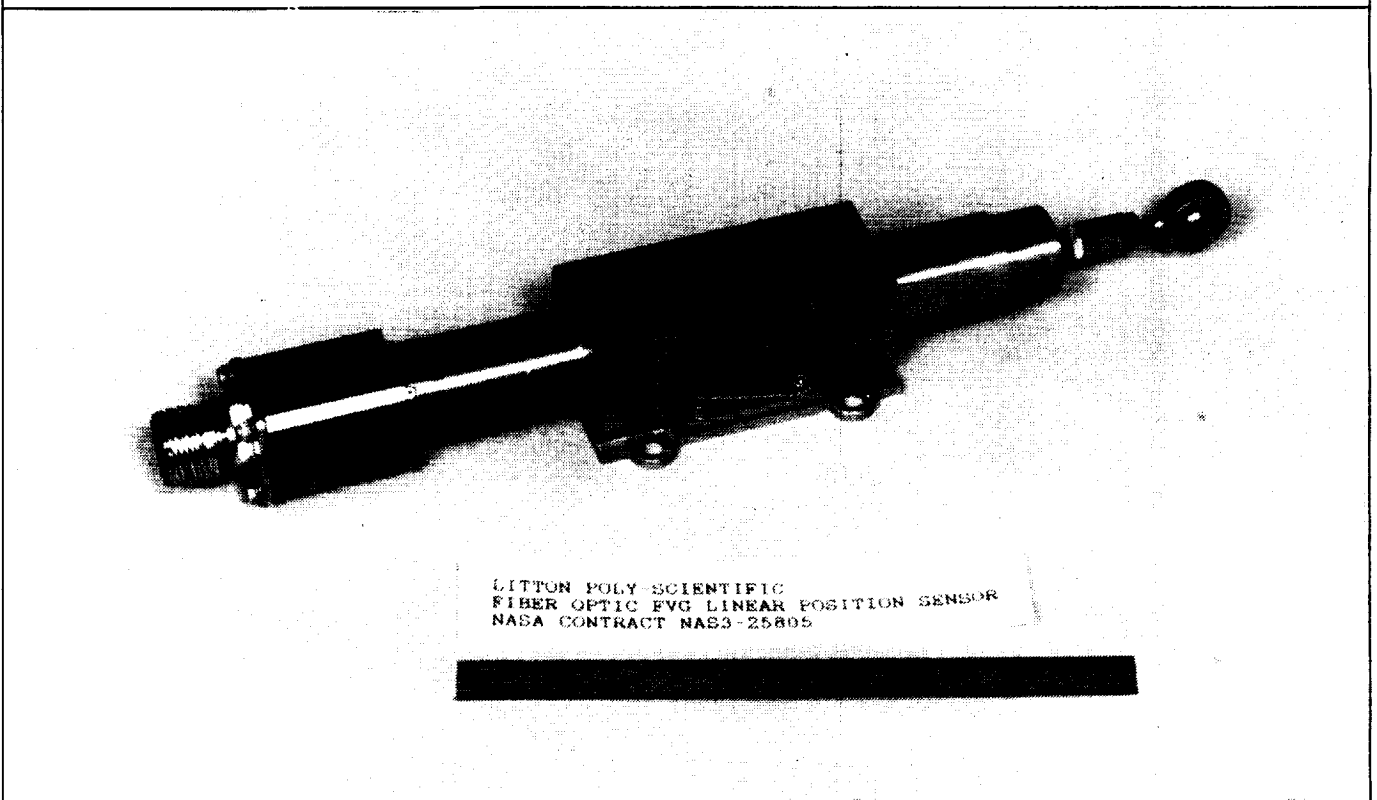


Figure 35 - Litton's Optical FVG Position Sensor

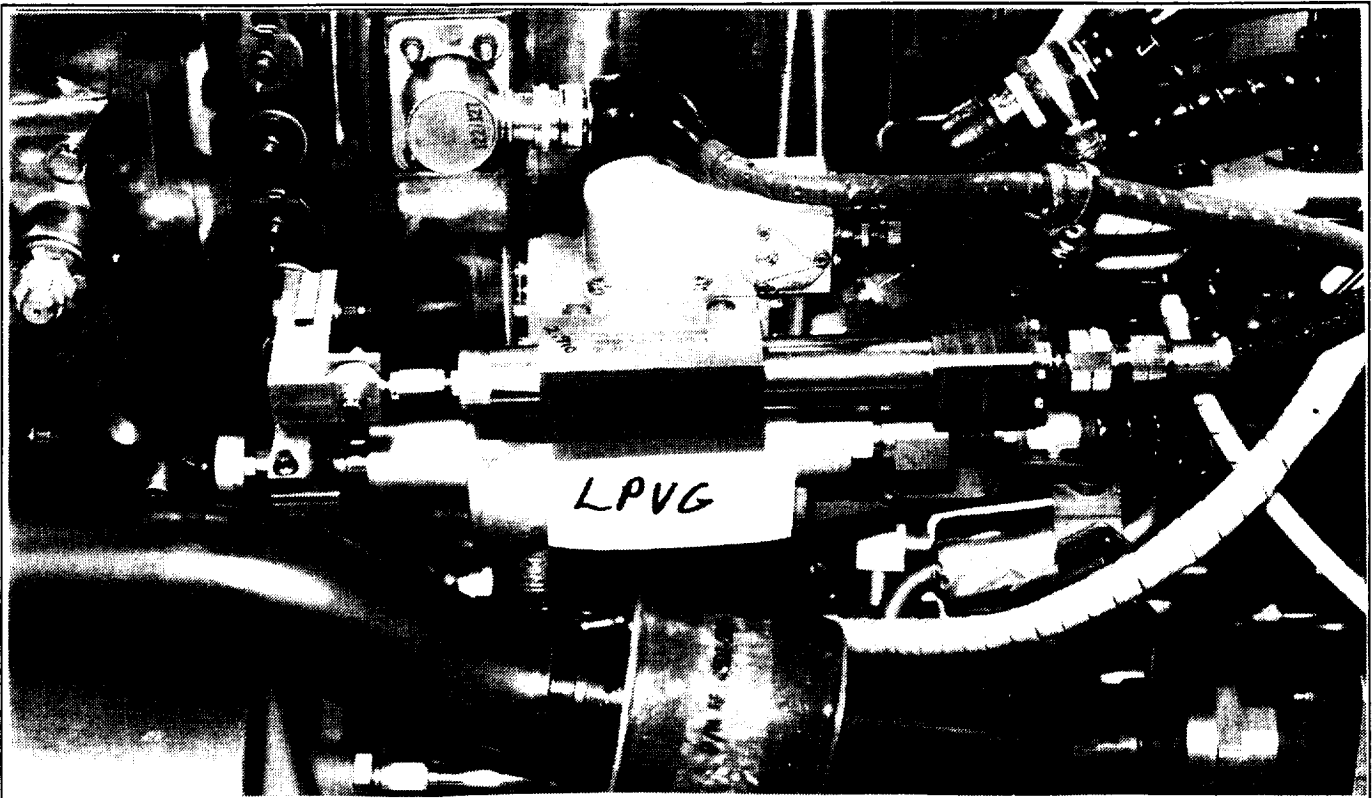


Figure 36 - Mounting of Optical FVG Position Sensor Onto F404 FVG Servo Block On NASA FOCSI Program

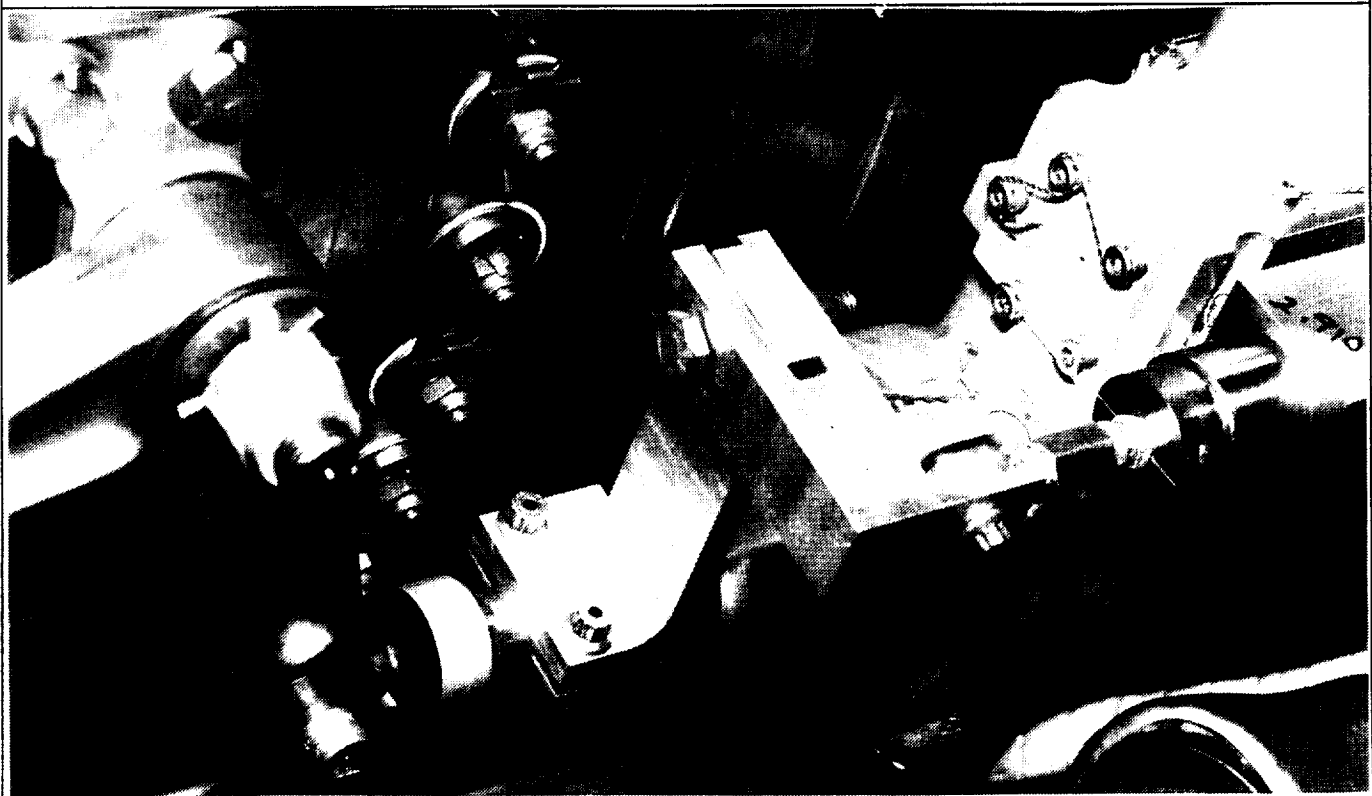


Figure 37 - Linkage Attaching Rod of Optical FVG Position Sensor To F404 FVG Actuator Piston

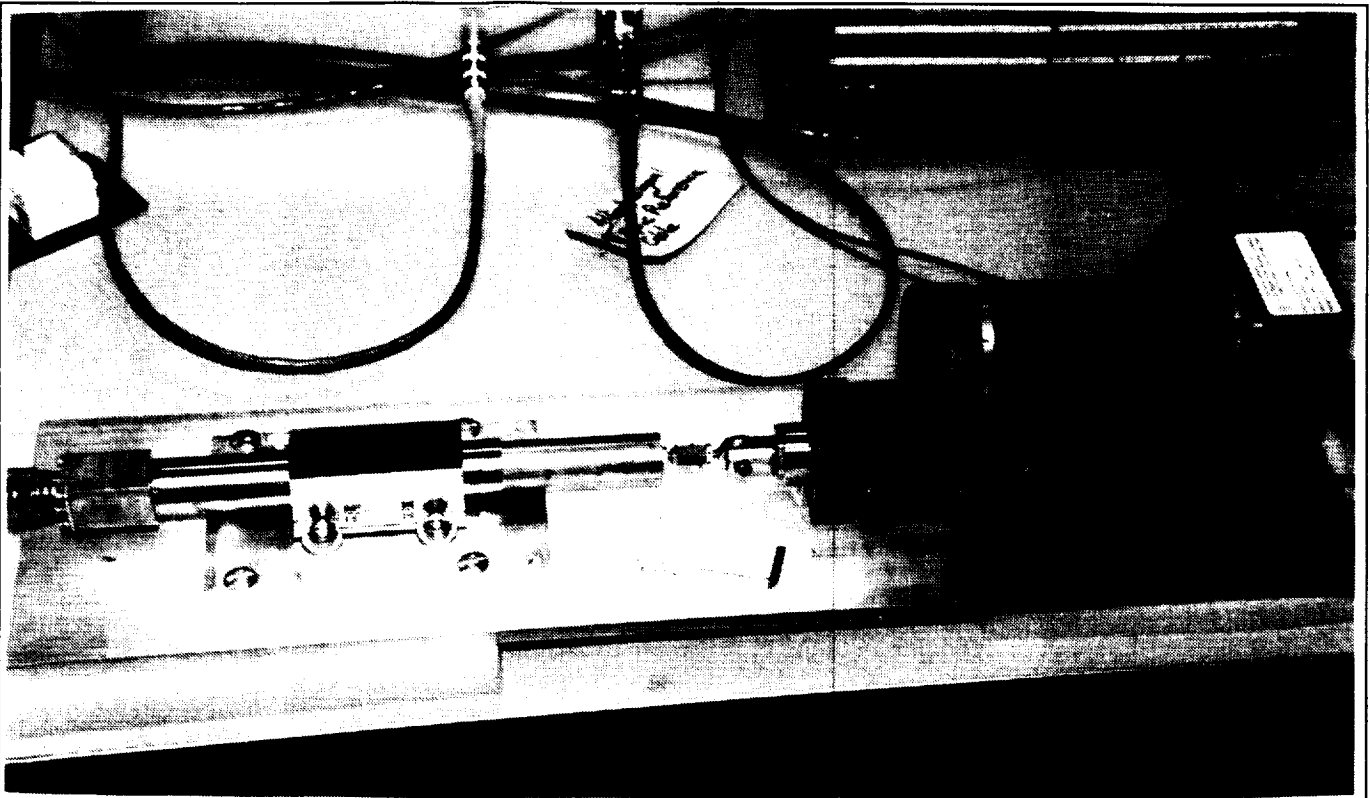


Figure 38 - Setup For Optical FVG Position Sensor Dynamic Testing

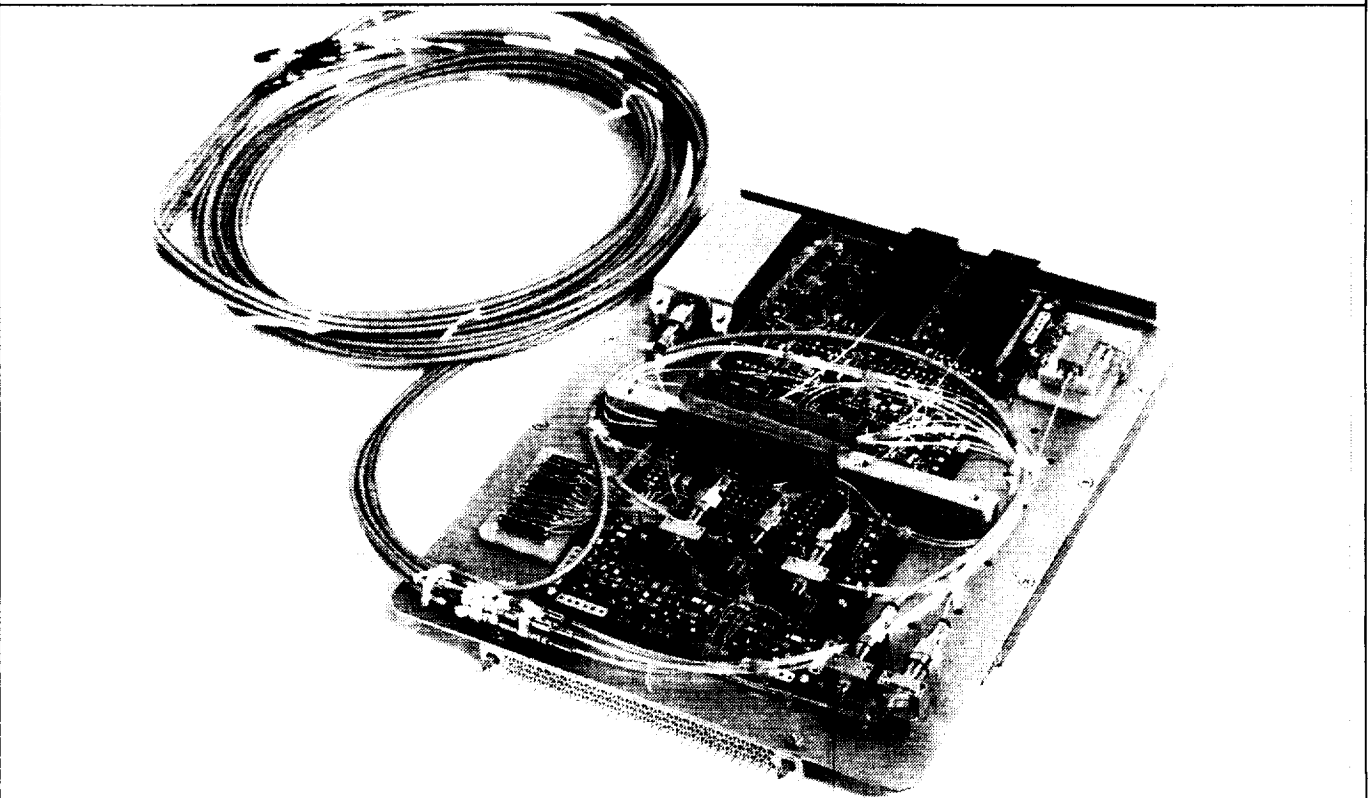


Figure 39 - Allied Signal's Electro-Optic Circuit Module - Side 1

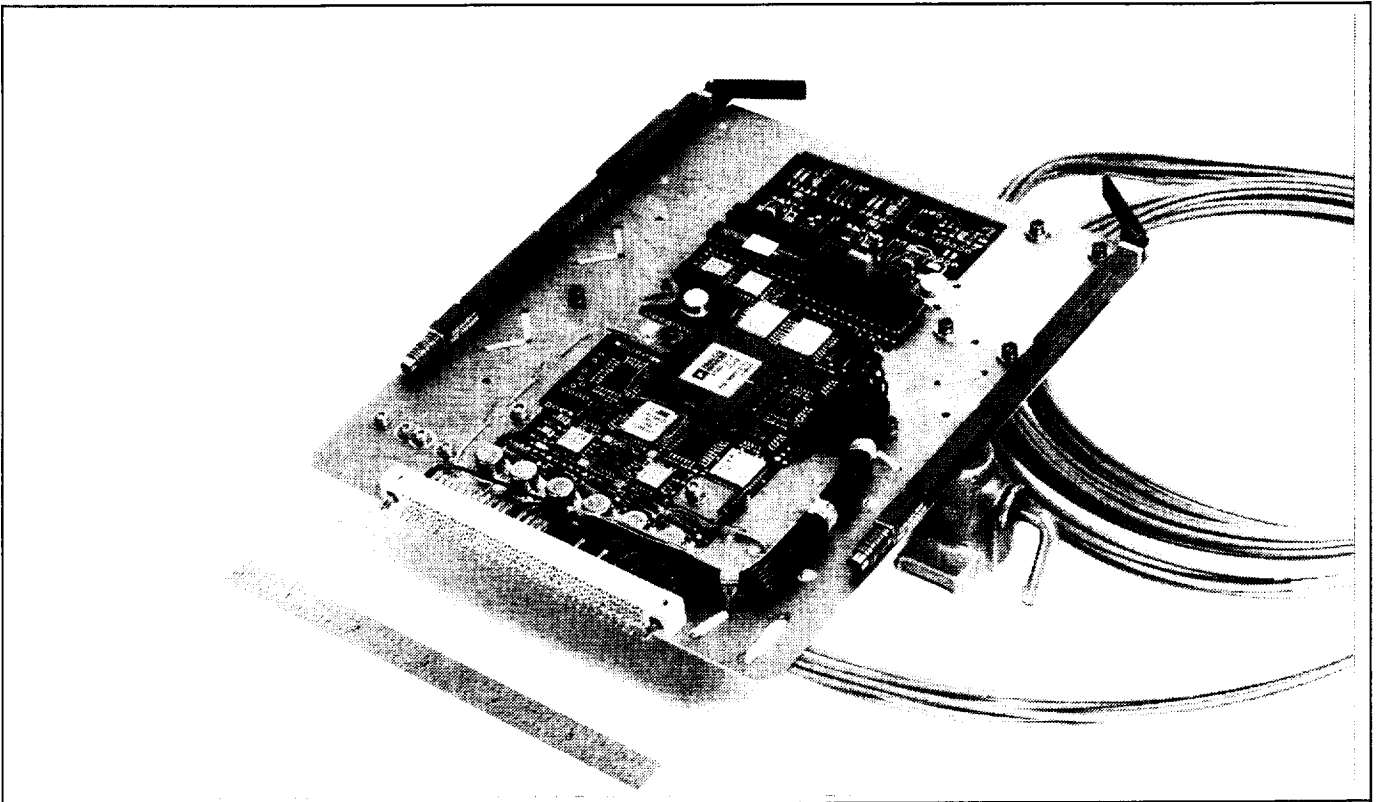
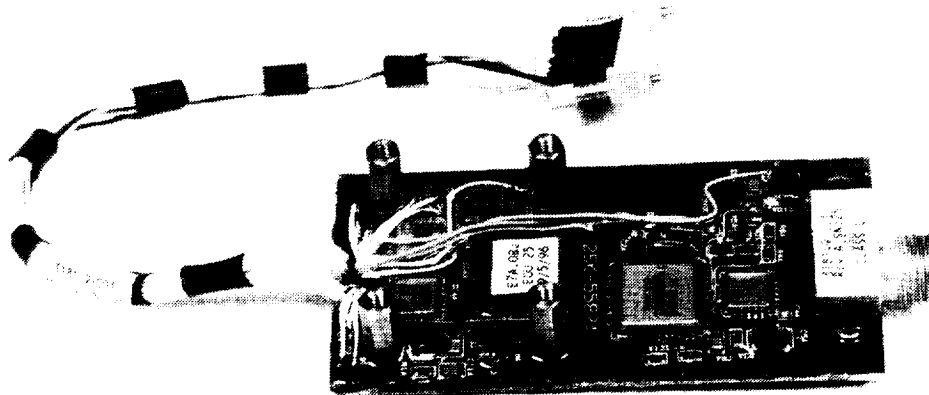


Figure 40 - Allied Signal's Electro-Optic Circuit Module - Side 2



Conax Electro-Optics Processor For
Optical T5 Probe / Harness Assembly

Figure 41 - Conax Buffalo's Electro-Optic Circuit Module

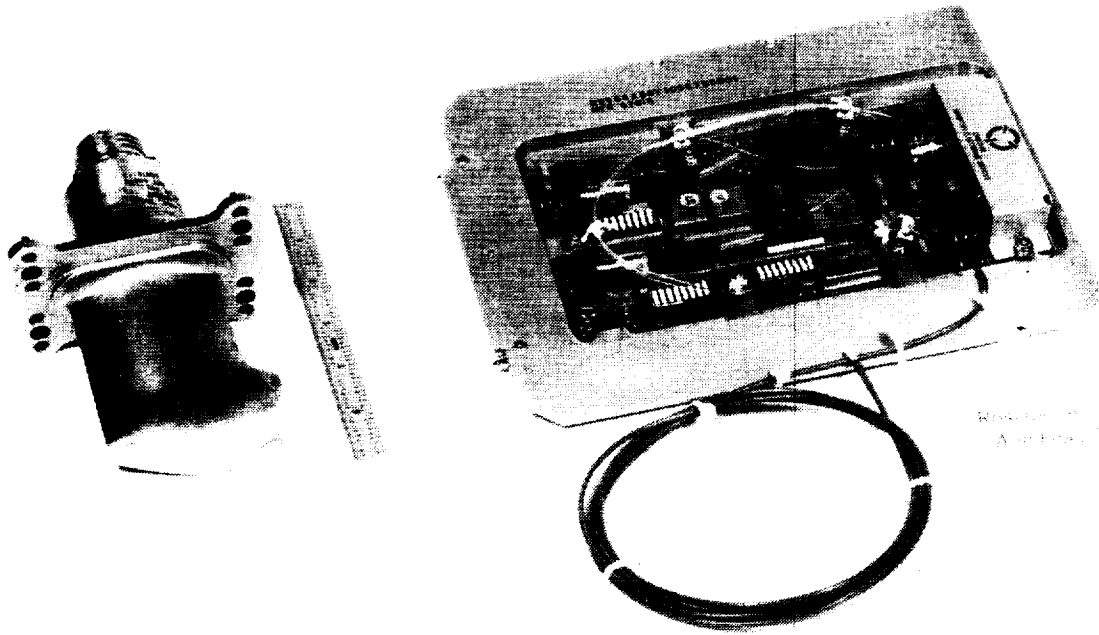


Figure 42 - Rosemount's Electro-Optic Circuit Module - Side 1

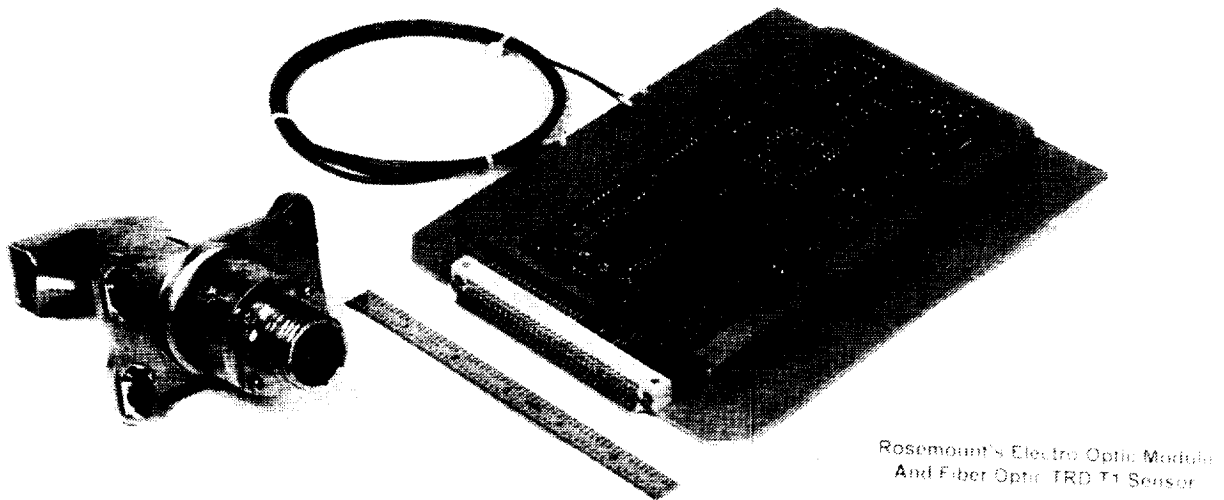


Figure 43 - Rosemount's Electro-Optic Circuit Module - Side 2

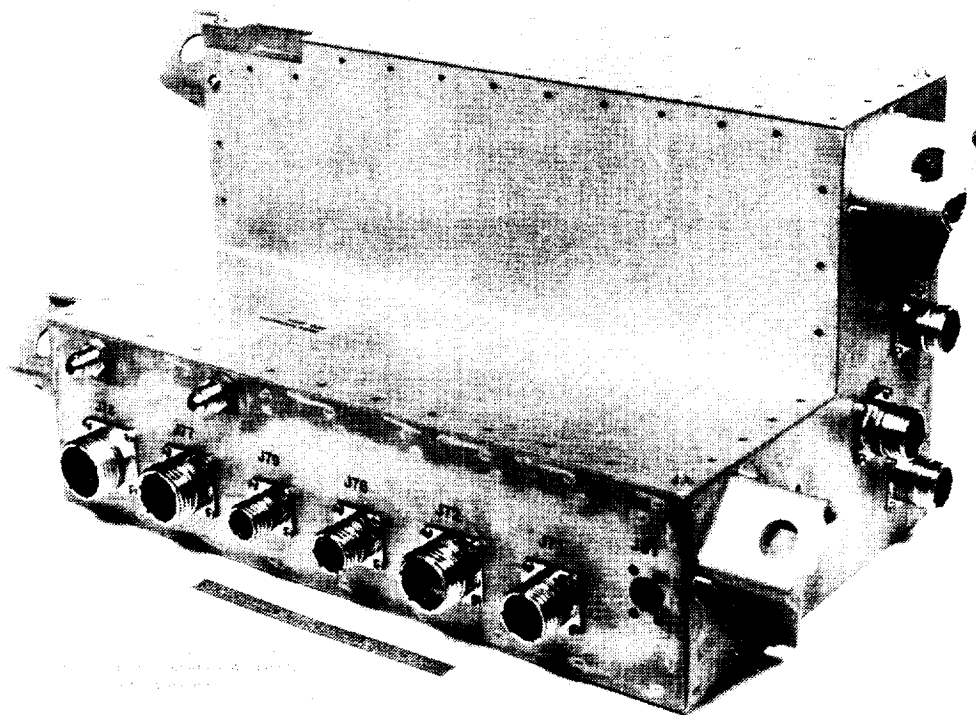


Figure 44 - EOI Chassis Showing Front and Side Connector Panels

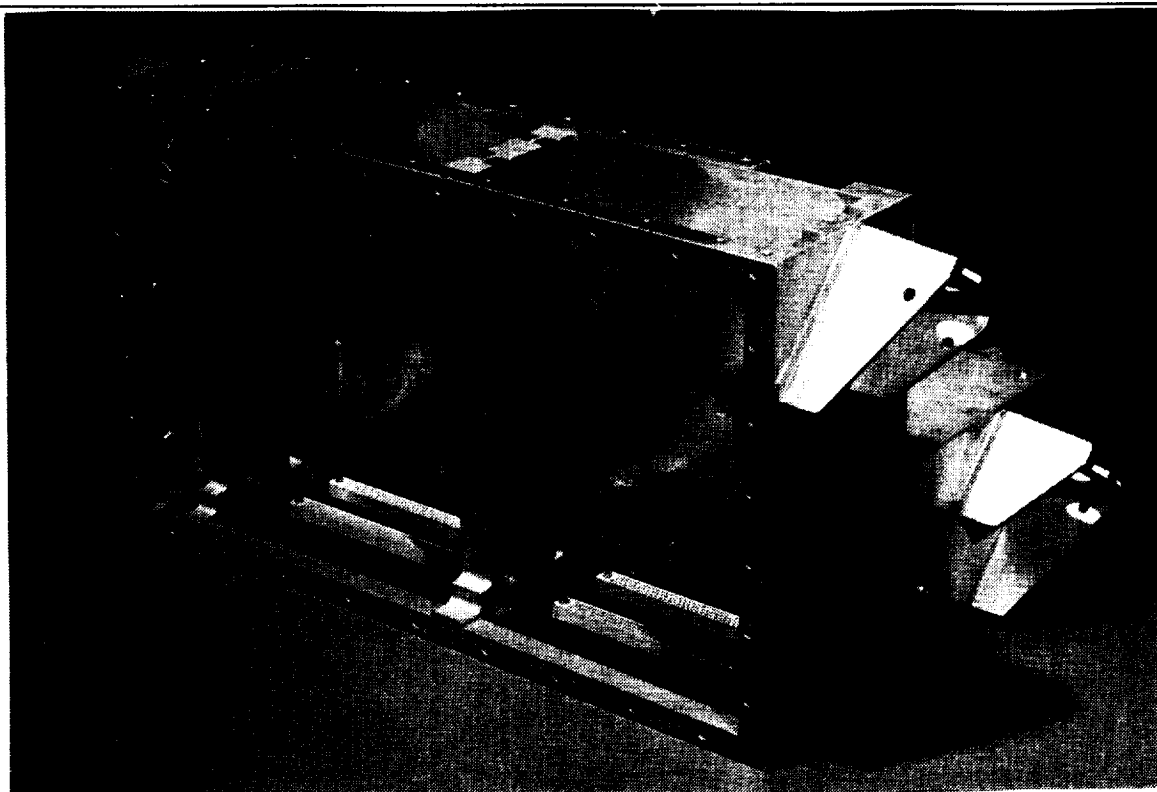


Figure 45 - EOI Chassis Showing Card Cage Volume and Installed Motherboard

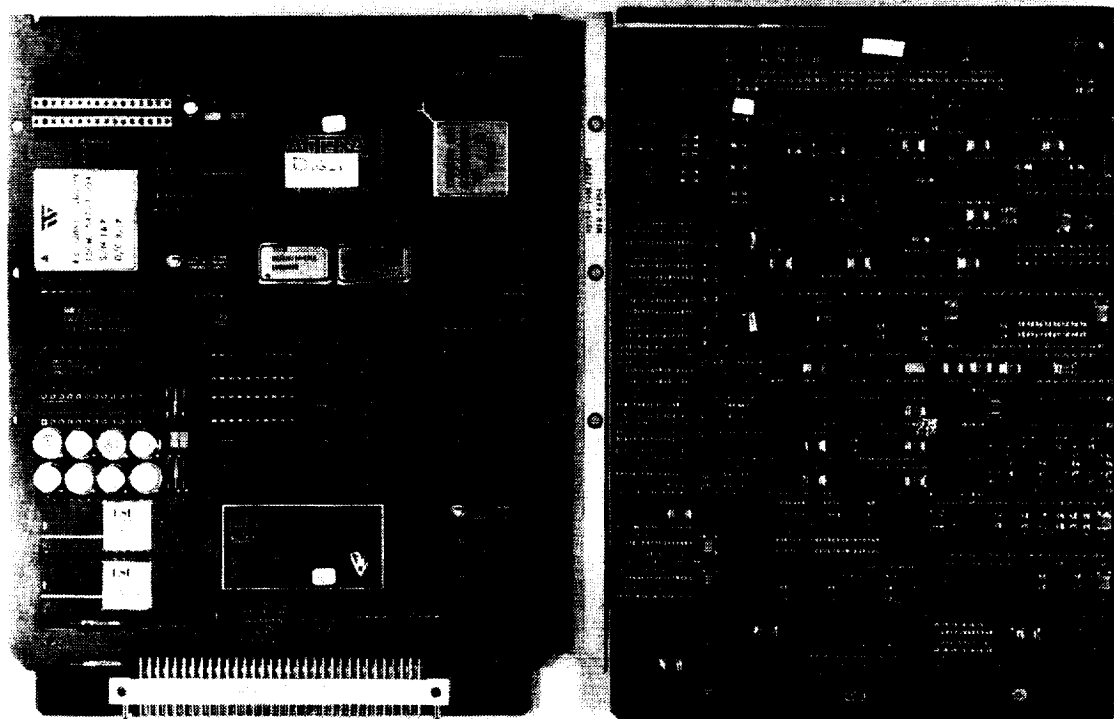


Figure 46 - The Lockheed Martin Digital Circuit Module

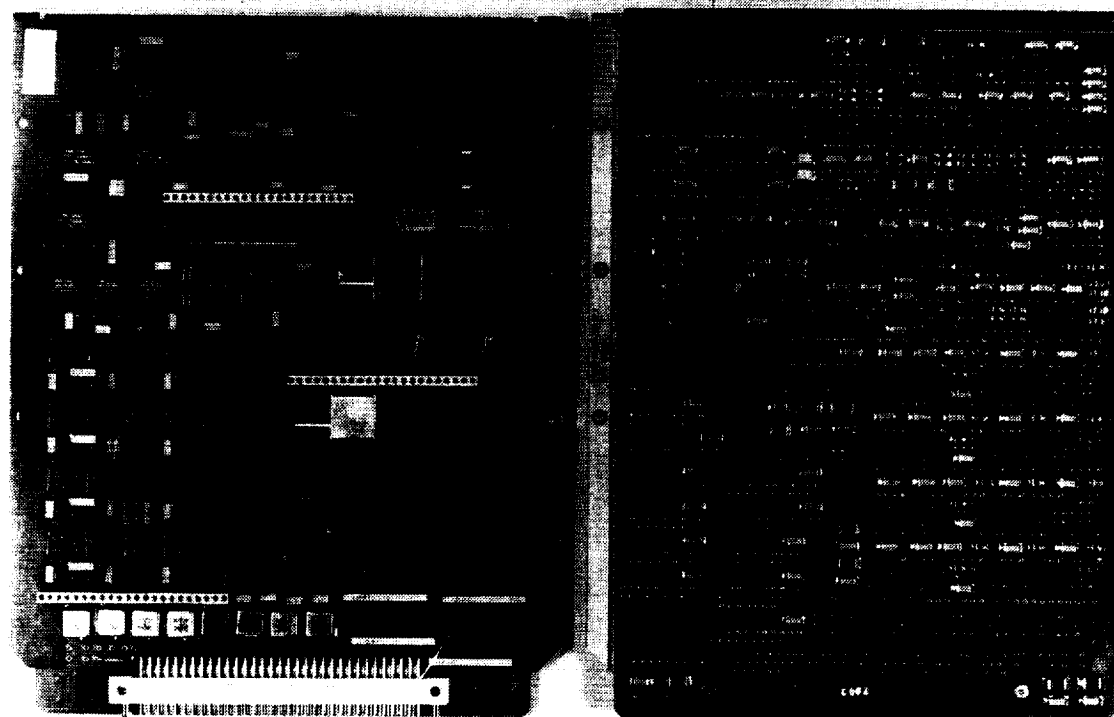


Figure 47 - The Lockheed Martin Analog Circuit Module

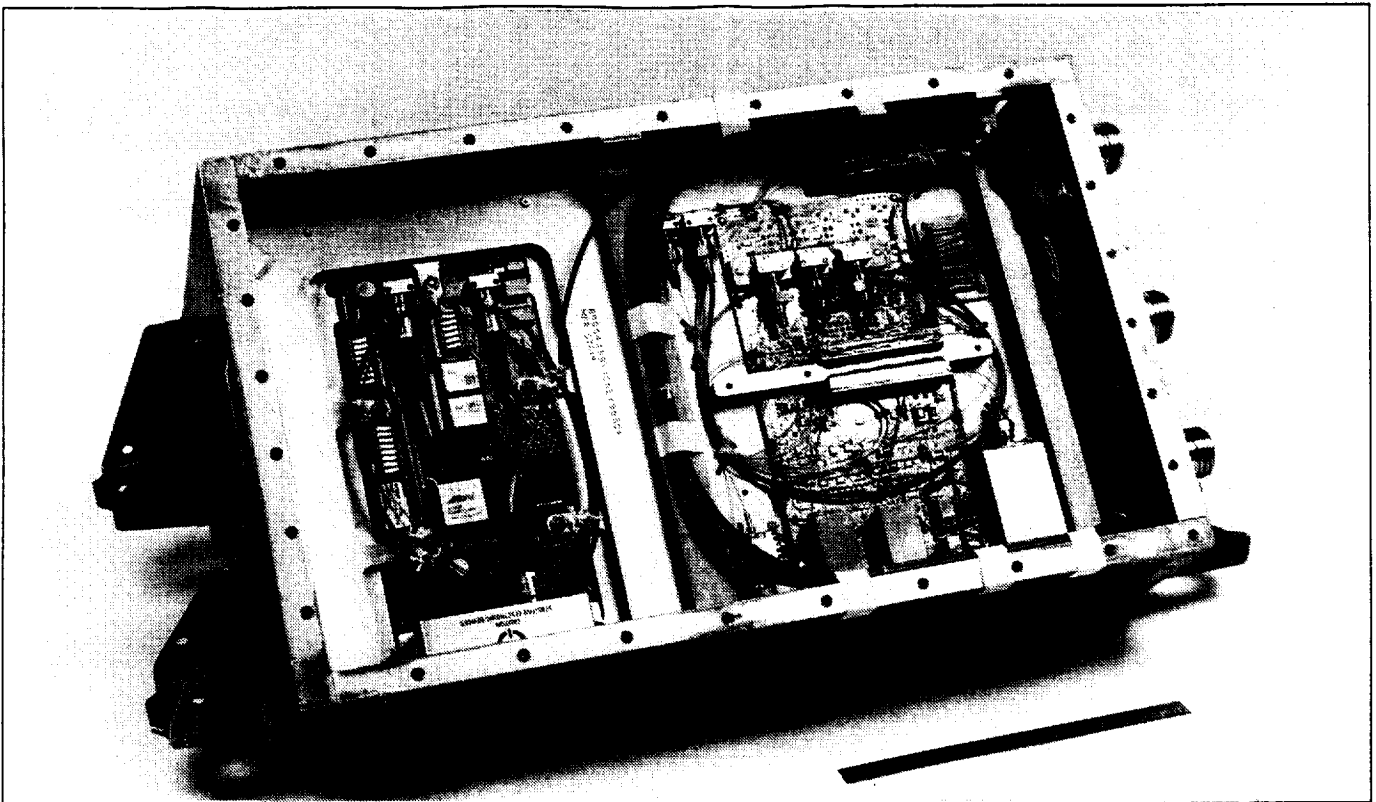


Figure 48 - The Rosemount and Allied Signal Electro-Optic Modules Mounted In the EOI Assembly

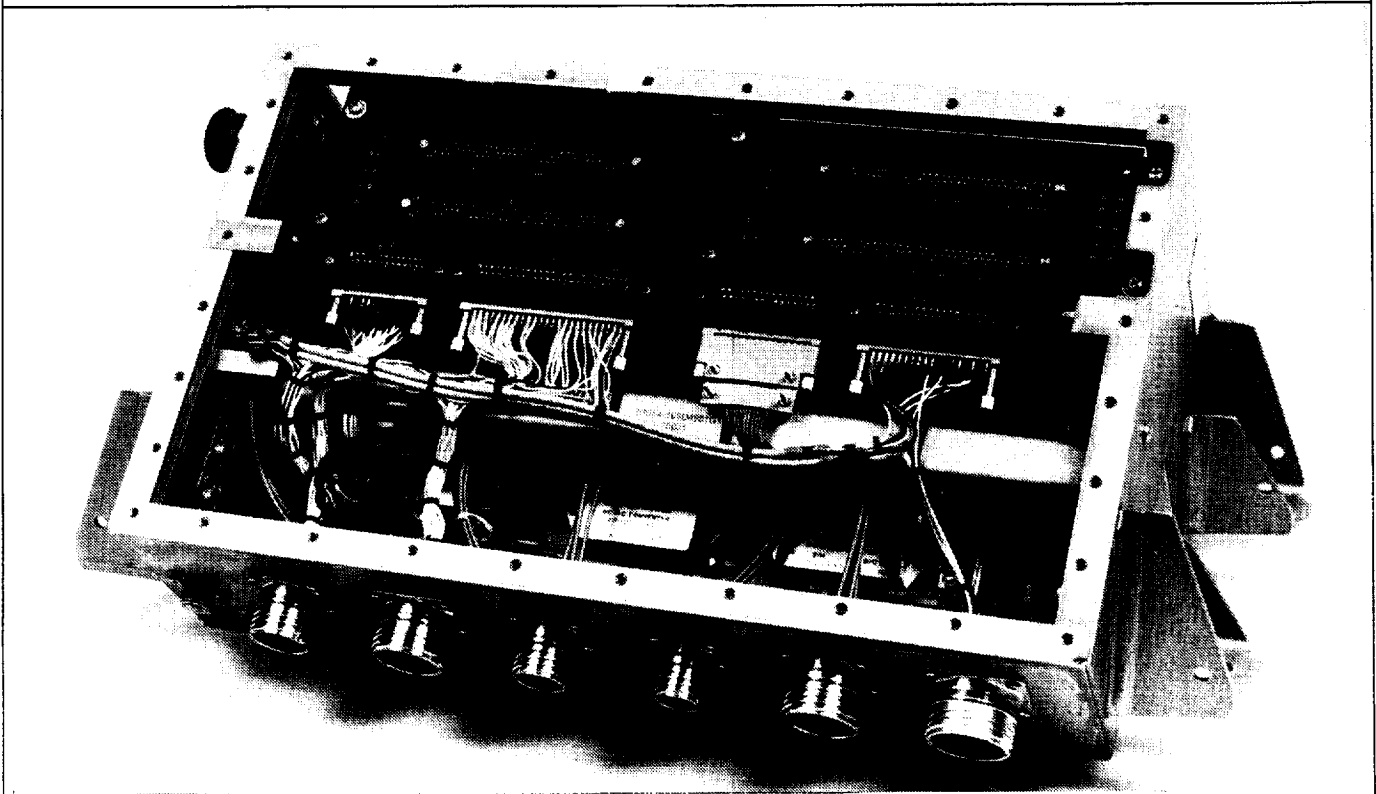


Figure 49 - The EOI Assembly Showing the Motherboard and Connector Interfaces

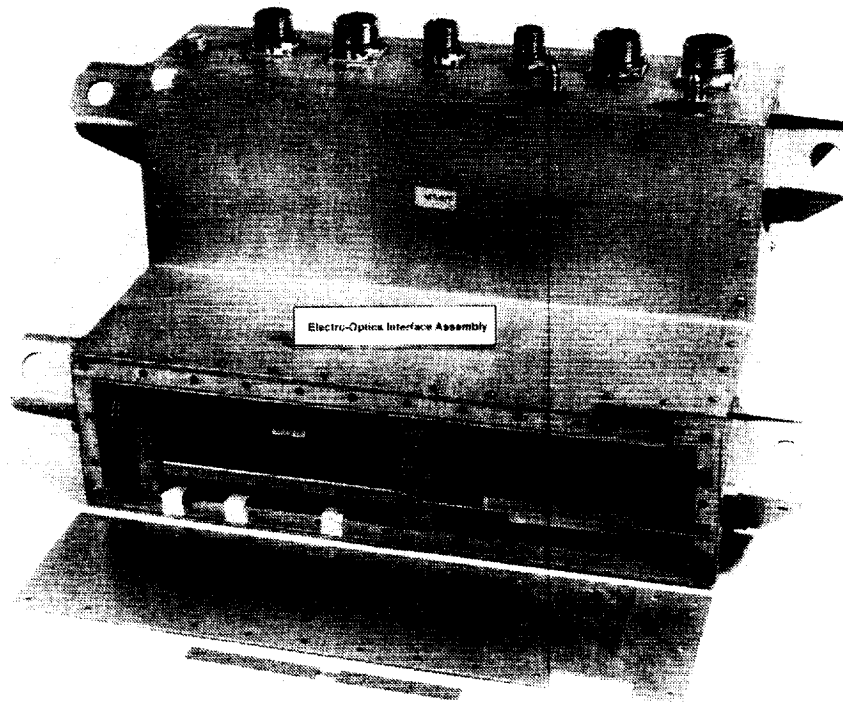


Figure 50 - EOI Assembly Showing Access To the Circuit Modules

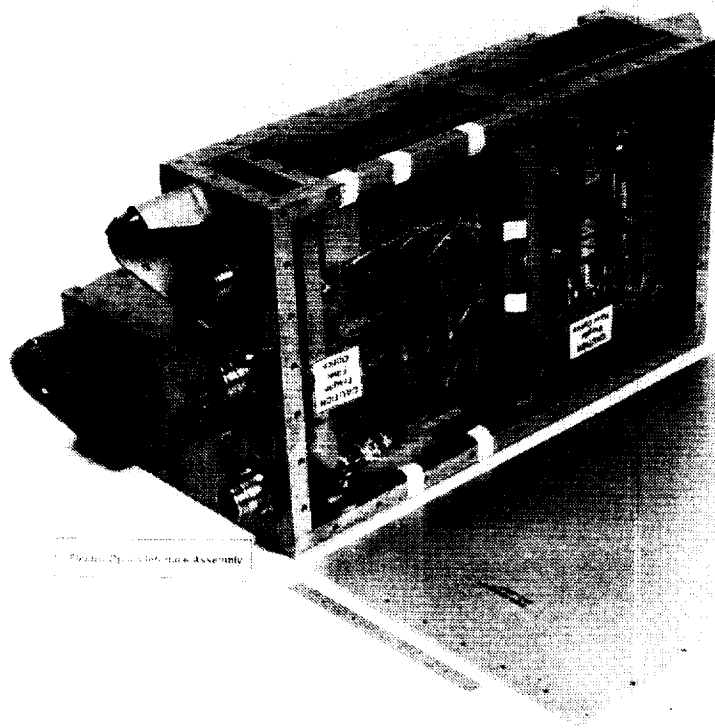


Figure 51 - EOI Assembly Showing the Installed Card Cage

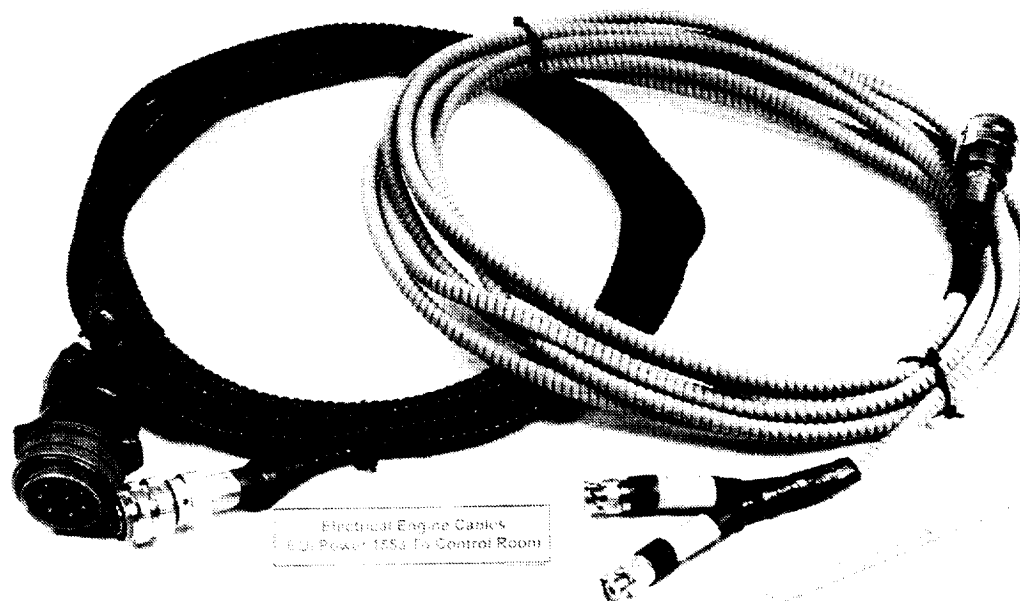


Figure 52 - Electrical Engine Cables - EOI Power/1553 To Control Room

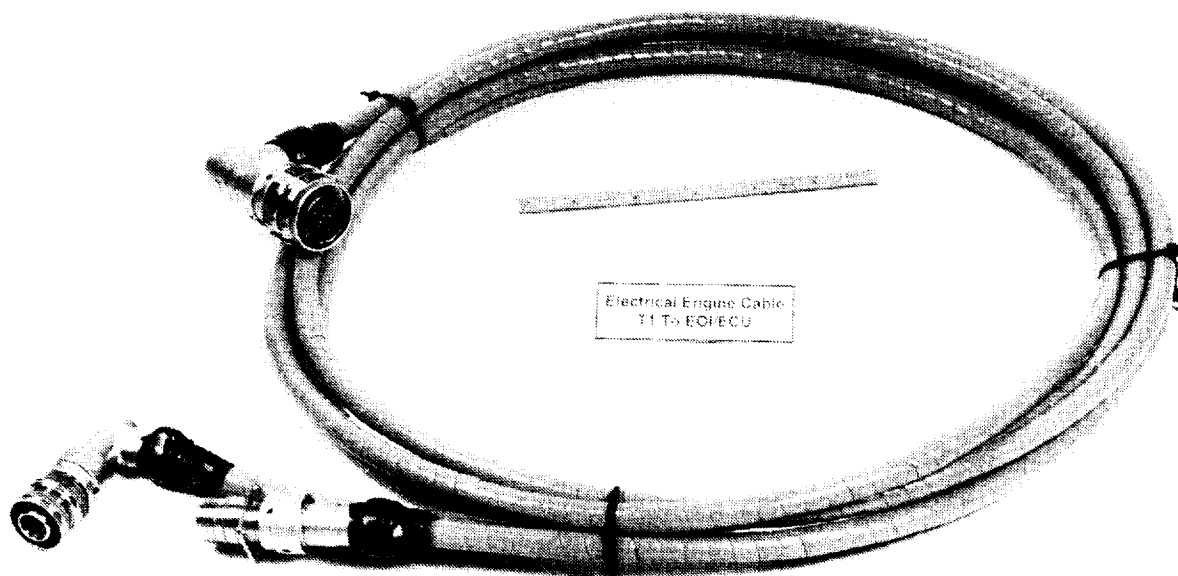


Figure 53 - Electrical Engine Cable - TI To EO/ECU

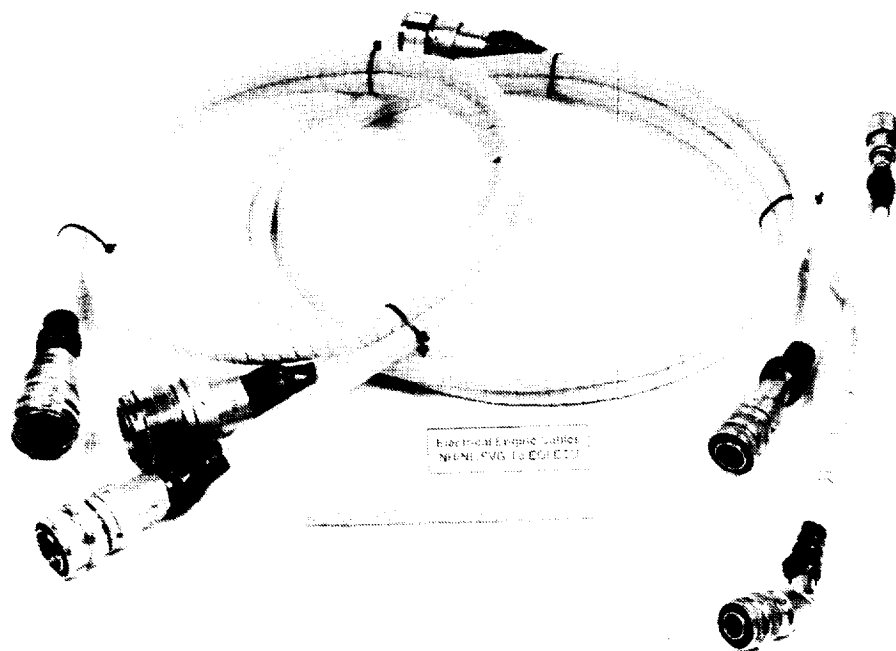


Figure 54 - Electrical Engine Cables - NH/NL/FVG To EOI/ECU

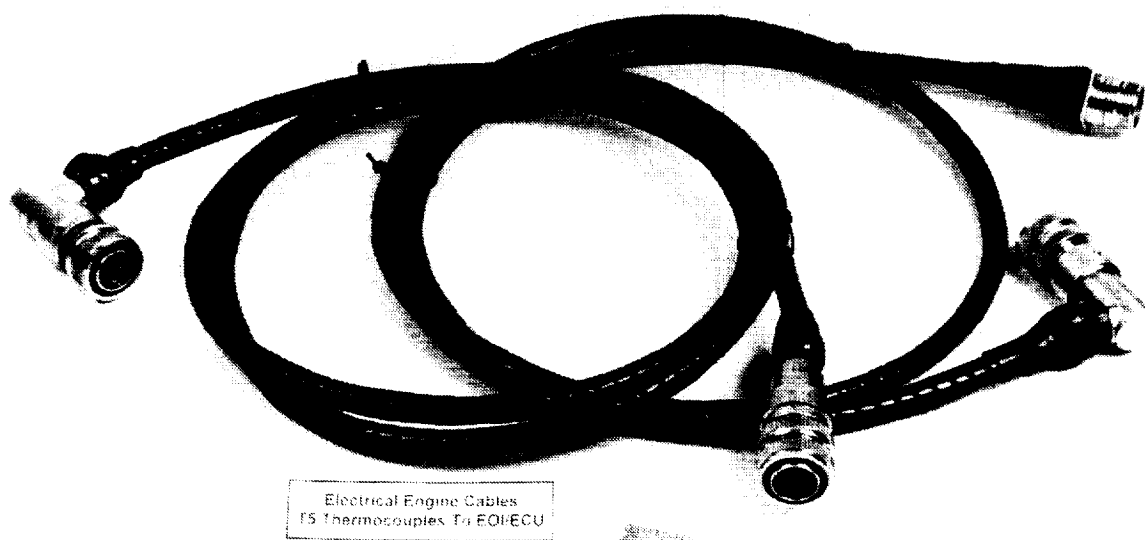


Figure 55 - Electrical Engine Cables - T5 Thermocouples To EOI/ECU



Figure 56 - Fiber Optic Cable Assembly, EOI/J77 To Optical T1 and NH Sensors

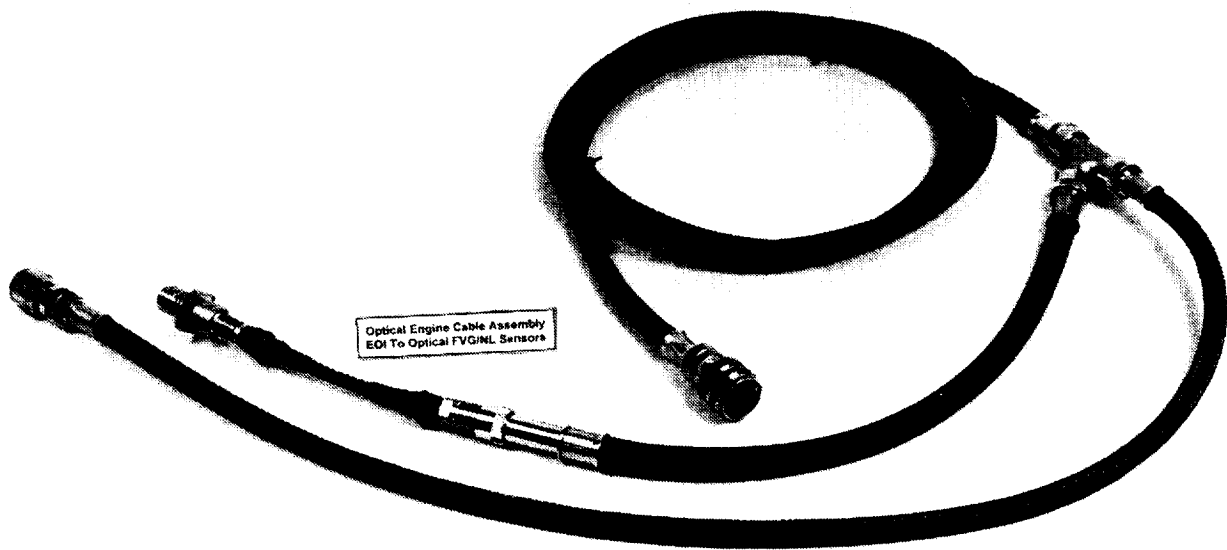


Figure 57 - Fiber Optic Cable Assembly, EOI/J76 To Optical NL and FVG Sensors

APPENDIX -B

ABBREVIATIONS

A8	Variable Exhaust Nozzle (VEN) Area
AB	Afterburner
BIT	Built-In-Test
CCD	Charge-Coupled Device
ECU	Electrical Control Unit
EOI	Electro-Optics Interface
EOU	Electro-Optics Unit
FEP	Fluorinated Ethylene Propylene
FOCSI	Fiber Optic Control System Integration
FVG	Fan Variable Geometry
HPT	High Pressure Turbine
IRP	Intermediate Rated Power (Maximum Non-Augmented Thrust)
LPT	Low Pressure Turbine
LVDT	Linear Variable Differential Transformer
NA	Numerical Aperture
NH	High Pressure Rotor Speed
NL	Low Pressure Rotor Speed
NVM	Non-Volatile Memory
PS3	Compressor Discharge Static Pressure
RAM	Random Access Memory
RTD	Resistive Thermal Device
TC	Thermocouple
TRD	Time Rate of Decay
T1	Engine Inlet Air Temperature
T5	Turbine Exhaust Gas Temperature
WDM	Wavelength Division Multiplexing
WFM	Main Burner Fuel Flow

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE August 1998		3. REPORT TYPE AND DATES COVERED Final Contractor Report
4. TITLE AND SUBTITLE Optical Closed-Loop Propulsion Control System Development			5. FUNDING NUMBERS WU- 519-30-53 NAS3- 26617	
6. AUTHOR(S) Gary L. Poppel				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) General Electric Aircraft Engines Cincinnati, Ohio 45215			8. PERFORMING ORGANIZATION REPORT NUMBER E-11272	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191			10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA CR-1998-208416 R98AEB237	
11. SUPPLEMENTARY NOTES Project Manager, Robert J. Baumbick, organization code 5520, (216) 433-3735.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Category: 07 This publication is available from the NASA Center for AeroSpace Information, (301) 621-0390.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) The overall objective of this program was to design and fabricate the components required for optical closed-loop control of a F404-400 turbofan engine, by building on the experience of the NASA Fiber Optic Control System Integration (FOCSI) program. Evaluating the performance of fiber optic technology at the component and system levels will result in helping to validate its use on aircraft engines. This report includes descriptions of three test plans. The EOI Acceptance Test is designed to demonstrate satisfactory functionality of the EOI, primarily fail-safe throughput of the F404 sensor signals in the normal mode, and validation, switching, and output of the five analog sensor signals as generated from validated optical sensor inputs, in the optical mode. The EOI System Test is designed to demonstrate acceptable F404 ECU functionality as interfaced with the EOI, making use of a production ECU test stand. The Optical Control Engine Test Request describes planned hardware installation, optical signal calibrations, data system coordination, test procedures, and data signal comparisons for an engine test demonstration of the optical closed-loop control.				
14. SUBJECT TERMS Optical engine controls; Control by light; Optical sensors			15. NUMBER OF PAGES 78	
			16. PRICE CODE A05	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	